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URBAN STREET CLEANING

POLYTECHNIC INSTITUTE OF BROOKLYN

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NATIONAL ENVIRONMENTAL RESEARCH CENTER

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This report presents the results of the analysis of mechanized street cleaning in urban areas. It includes the description of a data bank that contains detailed information on a blockside basis for a 300 block area. On the basis of these data the strong interrelationship between sweeper routes and no-parking regulations is established. It is then shown that the effectiveness of street cleaning by mechanical brooms is limited by the presence of illegally parked cars along curbs. Analytical models that assess the degradation of performance are developed for both metered and non-metered zones, and for any distribution of illegally parked cars. A model that relates enforcement to expected level of compliance is developed and validated with actual data. The effects of deterministic and random enforcement policies are analyzed, and a class of implementable policies that yields satisfactory results is presented. Optimal feedback policies that tend to minimize the cost of manpower while maximizing the level of compliance are derived. These results are used to determine routes and schedules that increase the effectiveness of enforcement officers. A litter generation model based on the System Dynamics methodology is developed and used to evaluate different operating conditions for commercial and residential areas.

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URBAN STREET CLEANING

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FOREWORD

Man and his environment must be protected from the adverse effects of pesticides, radiation, noise and other forms of pollution, and the unwise management of solid waste. Efforts to protect the environment require a focus that recognizes the interplay between the components of our physical environment--air, water, and land. The National Environmental Research Centers provide this multidisciplinary focus through programs engaged in

- studies on the effects of environmental contaminants on man and the biosphere, and
- a search for ways to prevent contamination and to recycle valuable resources.

The purpose of the investigation was the analysis of urban street cleaning and the evaluation of possible policy changes that would lead to cleaner streets. To this effect, data from a specific experimental district were developed and validated, and alternative policies were tested.

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Director
National Environmental
Research Center, Cincinnati

ABSTRACT

This report presents the results of the analysis of mechanized street cleaning in urban areas. It includes the description of a data bank that contains detailed information on a blockside basis for a 300 block area that constitutes District Nine of the NYC Department of Sanitation. On the basis of these data the strong interrelationship between sweeper routes and no-parking regulations is established. It is then shown that the effectiveness of street cleaning by mechanical brooms is limited by the presence of illegally parked cars along curbs. Analytical models that assess the degradation of performance are developed for both metered and non-metered zones, and for any distribution of illegally parked cars. It follows that enforcement of the no-parking regulations is essential in urban areas. A model that relates enforcement to expected level of compliance is developed and validated with actual data. The effects of deterministic and random enforcement policies are analyzed, and a class of implementable policies that yields satisfactory results is presented. Furthermore, optimal feedback policies that tend to minimize the cost of manpower while maximizing the level of compliance are derived. These results are used to determine routes and schedules that increase the effectiveness of enforcement officers. Finally, a litter generation model based on the System Dynamics methodology is developed and used to evaluate different operating conditions for commercial and residential areas.

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SECTION I

CONCLUSIONS

The purpose of the investigation was the analysis of urban street cleaning and the evaluation of possible policy changes that would lead to cleaner streets. To this effect, data from a specific experimental district were collected and analyzed, simulation models were developed and validated, and alternative policies were tested. The following conclusions, based on the analysis presented in Sections III-X, were drawn.

The current level of service, as measured by scheduled frequency of sweeping, is adequate but not well matched to the needs of the city; while some blocks are swept more often than necessary, others need increased service. There is a very definite need for reallocation of resources, i.e., not more sweepers but new sweeper assignments designed to satisfy community needs.

New, improved sweeper routes should be designed only after the level of service that is required to keep a district clean has been established. Routing procedures should take into account the effect of the attendant no-parking regulations on the temporal and spatial distribution of legal parking spaces in the district. Inequitable distribution of legal parking spaces is one of the factors that lead to high levels of noncompliance to no-parking regulations.

There is no need to ban parking in all 8-11 a.m. Alternate Side of the Street Parking zones prior to 9 a.m. However, it may be necessary to extend the period for sweeping metered zones from one hour to one hour and a half, preferably from 7:30 to 9:00 a.m.

The presence of illegally parked cars causes a severe degradation in the in the effectiveness of street cleaning by mechanical brooms. For effective service the compliance to the no-parking regulation should be kept at 80% or higher.

Severe degradation of performance also occurs if the broom operator does not make an effort to keep the length of curb bypassed because of illegally parked cars to a minimum.

In order to keep compliance at the desired high level long-term enforcement policies must be instituted. The issuance of summons must be random, but with predetermined average frequency that is commensurate with the needs of the specific area. For example, for the commercial metered area studied, enforcement should take place once every three days on the average. More frequent enforcement improves compliance only marginally but at high cost in manpower. Enforcement with a frequency of less than once every four days is ineffective to the extent that compliance drops below acceptable levels and the credibility of the enforcement policy is weakened.

The long-term effect of "saturation ticketing" for a period of several weeks is negligible; its only effect is to generate awareness through the media that a new effort to enforce the regulations is underway. Effective policies are those that can be sustained over long periods of time.

Systems based on fixed number of summonses that each enforcement officer must issue (quota system) are counterproductive. The expected number of summonses that an officer can issue within a specified time interval is a function of the route he follows, the enforcement strategy over previous weeks, and the characteristics of the particular district. A better approach that also permits indirect measurement of the effectiveness of the enforcement officer is to assign routes on the basis of expected levels of noncompliance obtained through a probabilistic simulation model that relates enforcement and compliance.

More efficient utilization of available manpower for enforcement is possible through the use of optimal feedback strategies valid over finite horizons. The strategies can be updated periodically by incorporating data from the immediate past. All computations necessary to determine the feedback strategies are off-line and can be done at a central location.

The effectiveness of partial enforcement along blocksides is negligible compared to the attendant cost in manpower.

The average litter of a commercial area is more sensitive to parameters that affect the generation of litter (e.g., litter basket density, litter basket pick-up interval, etc.) and less sensitive to parameters that affect the removal of already generated litter. On the other hand, residential area average litter is more sensitive to parameters that affect the removal of the generated litter and vice versa. It follows that efforts toward keeping the streets clean should be directed towards preventing the litter generation in commercial areas and towards removal of litter in residential areas.

The cleanliness of a blockside should not only be expressed in terms of the amount of litter present, but also in terms of distribution and size. A good measure, suitable for determining the frequency of sweeping (level of service) necessary to keep an area sufficiently clean, is the litter generation rate measured in cubic feet of litter per one hundred feet of curb per day.

SECTION II

RECOMMENDATIONS

This report contains the results of the first phase of a program for the analysis of urban street cleaning. Although the work presented herein is self-contained, there are several tasks that ought to be carried out. These tasks were originally scheduled for the second phase of the investigation.

The primary recommendation is that enforcement policies obtained and tested through simulation be implemented and tested in the field.

Validation of the litter generation model and establishment of its applicability to different urban districts is also recommended.

Finally, new routes should be designed and implemented that take into account both the service needs of the specific areas and the operational and budgetary constraints of the Sanitation Department. Recently developed computer algorithms should be used for the design of the new routes.

SECTION III

INTRODUCTION

The necessity for clean streets in an urban community has grown in importance in the last few years. The absence of litter and unsightly refuse is not only a significant factor in maintaining sanitary conditions, but has also become a measure of the quality of city life. For these reasons, the street cleaning operation carried out by the Department of Sanitation has long been a vital service to the people of New York City. However, while much is being done by the Department to increase the level of cleanliness of the streets, it is readily apparent that the final result does not depend only on the Department's operation, but also on the performance of several agencies and of the citizenry in general.

Street cleaning has features not shared by the related urban refuse collection and disposal processes. Most of the cleaning is done by mechanical brooms which follow scheduled routes that must be coordinated with no-parking regulations. This coordination is essential, since curbs scheduled to be swept must be free of parked cars or other impediments to the movement of the sweepers. The effect of the strong relationship between street cleaning and street parking is to introduce social and political considerations in the analysis of the problem.

Dirty streets can occur in spite of the most conscientious efforts of the sweeper operators and of management, if the no-parking regulations are not enforced, if the refuse collection is erratic or inadequate, if litter baskets are not available in adequate numbers or are not serviced sufficiently often, and if the rate of litter generation is too high in comparison to the resources available for street cleaning. In view of the complexity of the problem and in the absence of any previous published analytical work, an investigation was initiated in January, 1971 with the following three aims:

(a) To identify and analyze activities affecting mechanized street cleaning; to develop mathematical and simulation models with which present practice can be evaluated.

(b) To collect data from existing sources or from experiments and surveys in order to establish an extensive data base for a specific urban area.

(c) To evaluate possible policy changes that would lead to cleaner streets, subject to operational constraints.

An overriding consideration throughout the duration of the project has been that the recommendations be implementable. As a consequence, accurate data had to be used, problems could not be oversimplified for the sake of obtaining interesting analytical solutions, and, in addition to the views of the operating agencies, the views of the community had to be taken into account. Furthermore, the inclusion of managerial, environmental, and social aspects necessitated the decomposition of the overall study into five major tasks:

(1) Creation of a computer data bank.

The main role of the data bank is to contain a set of parameters which describe accurately the topology of the selected experimental urban district, the parking regulations, land use and census information, as well as indices that describe the amount of litter and its rate of generation. The bank was constructed with the capability for easy revision and for updating of the parameter values as more detailed and accurate measurements become available. The basic unit according to which data are stored is the blockside or blockface. In addition to providing the data base for other aspects of the project, the bank was used for obtaining computer generated tables indicating the distribution of parking regulations in the district, the curb length to be swept during each day and time period, the number of curb spaces made unavailable for parking and other statistics.

(2) Quantitative evaluation of the effect of illegally parked cars.

The effect of illegally parked cars along a sweeper's route is a key aspect in determining the effectiveness of mechanical brooms in cleaning the streets. On the assumption that a street is cleaned better if more of the curb is swept, an analytical model was developed that permitted for the first time a quantitative evaluation of the degradation of performance of street sweepers because of illegally parked cars. The actual length of curb swept is a function of compliance to no-parking regulations, spatial distribution of illegally parked cars, sweeper's maneuverability, and operator's skill. The last two quantities can be expressed in terms of the front and rear clearances required for bypassing a car parked illegally along the curb. This distance and the length of the car equal the length of unswept curb. However, when two or more cars are parked along a blockside, the unswept length is a nonlinear function of the intercar distances. An analytical expression, confirmed by experiments, for this interaction was derived and then two probabilistic models were developed that related the level of compliance to parking regulations to unswept curb length for various measures of operator's skill: a discrete one for metered zones and a continuous one for non-metered zones. With the use of efficient computational algorithms the expected length of curb that can be swept can be evaluated for any compliance level and any assumption regarding the spatial distribution of the cars along the blockside.

It should be noted that the results justified the belief of sanitation workers in the deleterious effect of illegally parked cars on street cleaning. Indeed, the need for close coordination between enforcement schedules and sweeper routing was demonstrated to management, and an effort was made to educate the public in the tradeoff between cleaner streets and leniency in the enforcement of the no-parking regulations. A series of presentations were given to various managerial groups of city agencies concerned with public services and to community groups in the experimental district.

(3) Enforcement policies for parking regulations.

The objective of this task was the determination of efficient, implementable enforcement policies, subject to operational and budgetary constraints, suitable for the enforcement of the no-parking regulations and for raising compliance to the desired level. An analytical model relating enforcement (input) and compliance level (output) was developed that yielded simulation results in agreement with the data. It is a probabilistic finite state machine model that is very versatile and can represent a wide variety of situations. The model was then used to study the effects of various types of enforcement strategies. It has been shown that random policies with predetermined statistics (such as average frequency of enforcement) are preferable to periodic ones with the same frequency. It was also shown that certain practices, such as saturation ticketing for a finite period of time, are ineffectual and wasteful; they are costly and their effect is short lived.

Because this work has implications and potential benefits for urban service beyond the street cleaning operation, and because enforcement, being labor intensive, is a major item in any budgetary consideration, the task was extended to the consideration of optimal policies. Optimal, or best, policies can be defined in a variety of ways to reflect specific situations. For example, in one case, best is defined in terms of minimum cost as measured by the number of manhours necessary to sustain a desired level of compliance.

(4) Routing of mechanical sweepers.

An effective route design must take into consideration the needs of the community both in terms of street cleaning and of the associated parking restrictions. Since in a district there is often wide diversity in litter generation rates, it is important that each block be scheduled to be swept a sufficient number of times each week to the extent that operational considerations permit it.

The determination of the appropriate frequency of sweeping for each blockside requires knowledge of the rate litter is generated. In the absence of a model describing the process by which litter is generated at any blockside, the required rates were obtained from a comprehensive survey of the experimental district. The survey also yielded insight in the litter generation process that was invaluable in carrying out the next task.

(5) Litter generation model.

Understanding of the litter generation process and development of a suitable simulation model are necessary preconditions for the formulation of effective policies for street cleaning. There are two types of policies: those aimed at reducing the rate with which litter is generated, and those which aim at the efficient removal of litter. The model is used to study and compare alternative policies in conjunction with the attendant costs and the institutional constraints.

The basic methodology used to construct the model is that of System Dynamics of J. W. Forrester[1]. This approach permitted the simultaneous consideration of a large number of highly interacting variables. The underlying mathematical formation is that of difference equations and the simulation language is DYNAMO.

The three primary determinants of the litter level on any blockside are land use, pedestrian traffic, and vehicular traffic. A fourth determinant, density of residential population, was shown from correlation analyses not to be a key one. The four important control variables are street sweeping, household and commercial waste collection frequency, litter basket distribution and servicing, and municipal regulations and their enforcement.

The litter generation model was implemented on a digital computer and many simulation experiments were carried out. The results were used to establish specific model inadequacies and identify processes for which more detailed empirical information was necessary. The final version of the model was used to study the effectiveness of litter baskets in residential or commercial areas, the trade-offs between increased enforcement and increased sweeping, as well as the sensitivity of the process to such parameters as frequency of refuse collection, waste storage capacity, etc.

In addition to the above tasks and in the spirit of interaction and continuing cooperation with the municipal agencies, the following projects were carried out: (1) a short study on the most effective allocation of new litter baskets provided to the experimental district by the city administration, (2) a short study analyzing various tree planting programs[2] in terms of the needs of the district and the existence of cost-sharing plans, and (3) a complete output with district statistics useful for planning an effective street lighting program as a crime prevention measure. All the above required only a small effort because of the availability of the centralized data bank. The reports were of great help to the local decision makers who do not have either the resources or the technical support for producing such studies at low cost at the local level.

SECTION IV

THE GEOGRAPHIC DATA BANK

The large volume of data required for the analysis of the street cleaning operation necessitated the creation of a centralized computer data bank. One of the first decisions that had to be made was the choice of the test area. It was decided that a Sanitation District would be the optimal choice since it is sufficiently small to allow for concentrated scrutiny and for relative ease in obtaining accurate measurements, and large enough to exhibit the necessary diversity. Furthermore, a Sanitation District is a well defined administrative unit, the key operational unit, in the chain of command of the Dept. of Sanitation: each Borough, headed by the Borough Superintendent, is divided into Districts, headed by a District Superintendent. Close cooperation could then be established with the line personnel of the selected District.

The basic unit according to which data are stored is the blockside or blockface. A typical block has four sides; there are blocks, however, with three, five, or more sides. Associated with each blockside is a vector containing information relevant to the street cleaning operation. The detailed description of the district and the data bank follows.

THE EXPERIMENTAL DISTRICT

The Washington Heights-Inwood district of Manhattan is ideally suited for the purposes of the investigation. The district is bounded by the Manhattan-Bronx borough line on the north, Harlem River and Harlem River Drive on the east, West 155th Street on the south and the Hudson River on the west. It includes Marble Hill on the North Shore of the Harlem River. This 14-block residential community was once the northern tip of Manhattan Island, and is still legally part of Manhattan. It became a part of the mainland at the turn of the century when the unnavigable

Spuyten Duyvil Creek was filled in and the Harlem River Ship Canal cut through Flatlands to the south. It is designated as Sanitation District 9 with complete district facilities located on 216th Street. The District is subdivided into five Sections numbered 91 to 95.

Washington Heights-Inwood-Marble Hill is also designated as Manhattan Community Planning District 12 (the planning district is a unit for which extensive records are kept by city agencies).[3,4] It contains approximately 300 blocks. The population has been decling, from 206,859 in 1950 to 199,357 in 1960, to 187,507 in 1970 (census figures). The population was 89% white, 11% non-white, while according to the 1970 census it is now 81.5% white and 18.5% non-white.

Public transportation in Washington Heights is good. The district is served by four subway lines (1,B,A, and AA) and the bus service on the avenues and major crosstown streets is adequate. The Trans-Manhattan Expressway, George Washington Bridge, Henry Hudson Parkway, and Harlem River Drive afford easy access to the Cross-Bronx and Major Deegan Expressways and the regional network of expressways. The Port Authority bus terminal outside the Trans-Manhattan Expressway, with connecting subway service below, is a secondary transportation center. It is used mostly by workers commuting from Bergen and Rockland counties to Manhattan.

There are numerous stores within easy walking distance from most residential blocks. On the whole, local retail establishments are holding their own, but due to growing reliance on outlying regional centers, there has been little growth in recent years.

Broadway is lined with small stores and restaurants, as are Dyckman and 207th Streets. There is some local commerce on Sherman and Nagle Avenues. Many of the tenements lining Amsterdam Avenue in the 150's and 160's have small stores on the ground floor, but this shopping area is thinning out.

The major commercial area is the 181st Street strip. Here, the shops are similar to those in other areas in the district, mostly small, family-owned food stores, specialty shops and restaurants, with a few chain stores here and there. Traffic on 181st Street is congested during peak shopping hours and on Saturdays, and many buses converge on 181st Street from the Bronx.

Many automotive and building material concerns are located along Sherman and Nagle Avenues. A few small manufacturers are scattered throughout the district. There is an industrial area at the Jumel Place section providing about 500 jobs, but it is in decline. The second industrial area is the one north of Sherman Creek between 10th Avenue and the Harlem River. A Transit Authority bus garage and subway yard, a sanitation garage and incinerator, police storage yards, a Department of Public Works garage and office, and a Consolidated Edison Company electric power plant are located in this area along with various industries providing more than 900 jobs.

The Heights also contains the large Columbia-Presbyterian Medical Center. The center is a complex of specialized diagnostic and treatment centers, schools offering instruction in several medical disciplines and various research institutions. In 1968 the center had more than 8,000 employees and represented a capital investment of more than 400 million dollars.

The district is surrounded by water on three sides and is ringed by park land. Yet despite the 530 acres of park land, a good portion of the greenbelt is inaccessible, cut off by railroad tracks and highways. As such, with the exception of a major office building complex, this district is essentially a city within a city. Furthermore, its well defined physical boundaries permit relatively easy measurement of incoming and outgoing traffic flow. Access is possible through eight bridges or the five intersections at 155th Street.

Manhattan Community Planning District 12, one of the 62 in New York City, has been declared one of several experimental districts. In the experiment, the local Neighborhood Action Program - one of six community centers of the Mayor's Office of Neighborhood Government - is allocated a budget ($525,000 for FY 1971) to be used for capital community expenditures at the discretion of the Citizen's Community Board, subject to the normal controls involving city expenditures. Furthermore, through the NAP offices close cooperation was established with the active Citizens' Sanitation Committee and other local groups.

In addition, the office of the Neighborhood Action Program has served as the focal point for university research in urban and societal problems. Researchers from the Polytechnic Institute of Brooklyn, from Columbia University, and from Yeshiva University have utilized this district for data collection and for experimental programs.

THE BLOCKSIDE CODE

The code number assigned to each blockside consists of four digits. The first three digits refer to the actual block itself. The numbering of the blocks begins with 000 at the southernmost end of the district and continues up to 333. The allocation of the code numbers is shown in Table 1. The code number assigned to each block is shown on a set of maps appended to this report (Appendix A.). The codes have been divided into five groups corresponding to the subdivision of District 9 into the five Sections 91-95.

The fourth digit identifies the specific side for each block. It also yields the direction of traffic along that side. Odd numbers correspond to traffic which is moving from a person's left to his right if he is facing the street with his back to the buildings along the blockside (clockwise). Even numbers correspond to traffic flowing from right to left (counterclockwise). The allocation of digits around a square block

Table 1. ASSIGNMENT OF BLOCK CODE NUMBERS

Section	Code Numbers	Unassigned Code Numbers
91	000 - 069	061 - 069
92	070 - 129	129
93	130 - 199	175, 176, 198
94	200 - 259	256 - 258
95	260 - 333	279, 288, 329

Special Cases

# 390 : Henry Hudson Parkway (155th St. - H. H. Bridge)
391 : Harlem River Drive (155th St. - Dyckman St.)
392 : Broadway Mall (155th St. - 168th St., both sides)
393 : Ft. Tryon Park

is shown in Figure 1. The arrows indicate the direction of traffic flow.

The digits 0 and 9 are reserved for five-sided, triangular, or otherwise unusually shaped blocks. A list of these blocks and the code assigned to each one of their sides can be found in Appendix B.

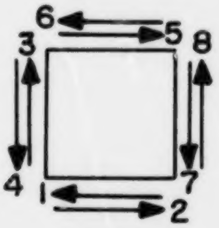


Fig. 1 Blockside and traffic flow code.

THE DATA

1. Curb Length - The curb length of each blockside, measured from corner to corner and rounded off to the nearest foot, was obtained from the detailed plates of the Manhattan Land Use Guide published by L. Bromley, New York, N. Y.

2. Street Width - The width of the street is measured from building line to building line and rounded off to the nearest foot. Knowledge of the zoning regulation permits the calculation of the width of the sidewalks and of the actual street width.

3. Parking Regulations - The parking regulations in effect on each blockside are stored in coded form. Because of the wide variety of regulations in existence in New York City and because many are governed by several regulations a code with up to three digits was required. The information was obtained from the records of the NYC Dept. of Traffic and crosschecked by surveying the district.

The code consists of one to three digits depending on the parking regulations assigned to each blockside. Most of the streets in the district have one parking regulation along each blockside; this is denoted by a simple single digit code. Those blocksideswith two parking regulations are identified by a two digit code. Finally, those blocksides with authorized or school parking are assigned a three digit code.

One digit code - The basic one digit code and the parking regulations assigned to it are defined in Table 2. Note that the digit 0 can only appear as part of a two digit code of the form x0, where x = 0,1,...,8. Digits 1 to 8 refer to Alternate Side of the street Parking (ASP) and 9 refers to metered zones.

Consider, for example, a block with a bus stop, a fire hydrant, some "No Parking Anytime" segments, and parking meters. The code "9" would be

Table 2. PARKING REGULATION CODES

Code	Regulation			
1	No Parking	:	Mon, Wed, Fri	8 AM - 11 AM
2	No "	:	Tue, Thu, Sat	" "
3	No "	:	Mon, Thu	" "
4	No "	:	Tue, Fri	" "
5	No "	:	Mon, Wed, Fri	11 AM - 2 PM
6	No "	:	Tue, Thu, Sat	" "
7	No "	:	Mon, Thu	" "
8	No "	:	Tue, Fri	" "
9	METERED PARKING (No Parking 8 - 9 AM)			
x0	NO PARKING permitted along the entire blockside due to various combinations of "No Parking Anytime" zones, Bus Stops, Hydrants. The first digit (x=1,2,...,8) indicates the day and time (as shown above) the blockside is scheduled to be swept. Special cases are coded as 0.			

assigned to the entire block; the bus stop, fire hydrant and the no parking zones are accounted for in the calculation of the "Illegal Parking Length."

Two digit code - There are several dozen blocksides in the district which have both metered and alternate side parking zones. They occur mainly on side streets off main commercial routes such as Broadway, St. Nicholas, etc. A two digit code is used to characterize these blocksides. One digit denotes the ASP regulation and the other is "9" to indicate the existence of meters, e.g. 19, 29, ..., 89, or 91, 92, ..., 98. The ordering of the two digits has significance. For instance, 19 means that if one moves in the direction of traffic along the blockside he encounters the M-W-F AM ASP regulation zone before the meters. Conversely, 91 means that a metered zone precedes the ASP regulation.

Three digit code - A three digit code indicates the presence of Authorized or School Parking. The "100" series is used for "No Parking from -- to -- Except Authorized Vehicles." Such regulations occur near hospitals, police precincts, some educational institutions, etc. The "200" series is used for "No Parking 7 AM - 4 PM School Days."

The code "100" indicates that the entire blockside has Authorized Parking. Similarly, "200" indicates that the entire blockside has School Parking. There are several blocks, however, where Authorized or School Parking coexists with other regulations. It is possible to denote such situations by placing the appropriate one or two digit code in the third, or second and third places, respectively, of the three digit code. For example, "108" is interpreted as a blockside with Authorized Parking and No Parking 11-2 on Tuesday and Friday. As another example, consider the code "291". This implies that three different regulations appear on that side of the block: metered parking (the 9), No Parking MWF 8 - 11 (the 1), and School Parking (the 2 in the leftmost position). Note that no information is given as to which regulation appears first along the blockside.

4. Illegal Parking Length - This is defined as the portion of the curb length in which it is illegal to park at all times. The length is computed from the basic data according to the following formula:

I.P.L. = Length of "No Parking Anytime" zones
+ " " "No Standing" zones
+ " " "No Parking 7 AM to 4 PM on School Days" zones
+ " " Bus Stops
+ 30 ft. per fire hydrant.

All the above lengths are measured in feet. Note that
(a) Driveways have not been included for lack of data;
(b) "Authorized Parking" zones have not been included since cars, albeit not all cars, can park;
(c) Overlap of fire hydrant zones with Bus Stop zones has not been taken

into account. However, the maximum error possible is 30 ft. per occurrence. The probability of error due to such an occurrence is very small if one considers that bus routes pass through commercial areas where metered parking or "No Parking Anytime" zones are prevalent.

5. Number of parking spaces - For non-metered areas the following formula has been used:

$$\text{No. of Spaces} = \frac{\text{Curb Length - Ill. Park. Length}}{24'}$$

where only the integer part of the quotient is used. For metered areas, the number of metered spaces is used.

6. Land use - Land use data were obtained from the New York City Planning Commission Map for 1969-70. Although the City Planning Commission has a coding system to indicate land use, a revised one was used that facilitated the storage of information in the computer data bank. The coding system used is shown in Table 3.

Since in each blockside more than one type of land use may be found, it was decided that sufficient accuracy will be obtained if a five digit code is used. Each digit represents the land use for approximately 20% of the length of the blockside. For example, if 80% of the length of the blockside has one-family detached homes (Code 7) and 20% retail commercial (Code 5), then the land use code for the blockside is 77775.

7. Litter rating - Prior to the design of actual routes, it is necessary that the cleanliness of an area be surveyed, since the frequency of sweeping of each blockside depends on the rate litter is generated. A three digit code was developed that expressed the information obtained from actual observation of each and every blockside in District 9. For details of the experimental procedure, see Appendix C.

The first digit represents the extent to which the blockside was littered

Table 3. LAND USE CODES

Data Bank		Map	
Code	Description	Code	Description
1	High density residential	6	Walk-up multiple
"	"	7	Elevator multiple
2	Industrial	9	Light industry
"	"	11	Heavy industry
3	Vehicular (P+D) traffic	1-P	Parking lot
"	"	10	Gas station
"	"	9-W	Warehouse
4	Offices, public inst.	8-0	Offices
"	"	12	Public buildings
5	Retail commercial	8	Retail commercial
6	Parks	2	Parks
7	Low density residential	3	1 family detached
"	"	4	1 " "
"	"	5	2 " walk-up
8	Vacant lot	1	Vacant lot
9	Transportation	13	Transportation

on the days it was surveyed. It can take one of three values:

(a) Code 1 : 0-15% of curb covered with litter;
(b) Code 2 : 15-40% " " " " " ;
(c) Code 3 : 41-100% " " " " " .

It should be noted that the scale is not linear, but it accentuates low litter levels. This resulted in desirable higher resolution of the "clean - not clean" threshold.

The second digit indicates, in coded form, an estimate of the physical size of the litter present along the curb.

(a) Code 1 : Small pieces of paper (candy wrappers, crushed cigarette packs), cigarettes, and other small objects;

(b) Code 2: Cans, bottles, milk cartons, and other objects of similar size;

(c) Code 3: Large objects such as tires, cartons, tree branches, etc. that cannot be swept by the mechanical brooms;

(d) Code 9: This number is used to indicate special circumstances such as inaccessibility of the blockside due to construction or "dead end," etc.

The third digit denotes the number of days between the time the blockside was last swept and the time it was surveyed. For example, blockside #0207 was given a rating of 212. This means that 15-40% of the curb was covered with small size litter and that two days had elapsed since it was last swept.

8. Litter Volume Rate - This is the estimated litter generation rate associated with each blockside in the district. The unit is cubic feet of litter per one hundred feet of curb per day. It was computed from the litter rating data via an algorithm described in Appendix C.

9. Census Data - The following data were taken directly from the 1970 U.S. Census[5,6] or from the Community Profile[7] prepared by the New York City Planning Commission from the Census information.

9.1 Census Tract Number
9.2 Census Block Number
9.3 Tract Population
9.4 Block Population
9.5 Median Age in Tract
9.6 Median Income in Tract
9.7 Number of Housing Units in Tract
9.8 Quality of Housing Units in Tract
9.9 Crowding Index of Tract

It should be noted that the correspondence between Census Blocks and geographic blocks is not exactly one-to-one, because the former are defined according to housing, while the latter are defined according to physical boundaries (curbs) that relate to street cleaning. The Census data are of limited usefulness because most of the information is provided for tracts. This is too large a unit for the described analysis of urban street cleaning.

A typical sample from the Data Bank is shown in Appendix C.

SECTION V

ANALYSIS OF EXISTING REGULATIONS AND PRACTICES

DISTRICT NINE[7]

Sanitation District 9 has one major facility located on Broadway and 215th Street which houses the district offices and all the trucks and other equipment. Only Section 92 has a separate facility on Broadway and 175th Street. A lot on 216th Street and behind the garage is used for the dumping of bulk refuse (furniture, appliances, etc.) by the residents and for the emptying of the hoppers of the mechanical brooms. The refuse is collected from the lot and transported to the Marine Transfer Station located on 135th Street and 12th Avenue. If this facility is overloaded, the trucks are driven to the Pelham Bay landfill. It takes one hour and 25 minutes for the round trip.

The physical resources allotted to District 9 for street cleaning were (1971-2) 6 Wayne Brooms, 4 Elgin Brooms, and 3 old Flushers. In 1972 arrangements were made for the purchase of two more brooms with funds from the Neighborhood Action Program. In general, equipment and men can be attached to or detached from a district by borough command according to need. In District 9 the allocation of equipment over 1970-72 has been fairly stable at the indicated levels. A very serious problem, however, has been the proper maintenance of the equipment. For example, over a three month period (July to September 1971) on the average 46% of the brooms were down. Recent changes in the procedures have decreased substantially the down time of the equipment[8].

The breakdown of the operating force in the district is as follows:

1 District Superintendent reporting to the Borough Commander;
19 Officers reporting to the Superintendent;
162 Men;
2 Clerks;
3 Mechanics including the garage foreman;
5 Permanently detached.

The district superintendent can only monitor the performance of the three mechanics; the garage foreman reports directly to the borough foreman. The men are organized in crews and the crews are assigned to one of the five Sections. There is an officer, the Section Foreman, responsible for each Section. As a result, the sweeping assignments and the associated broom routes correspond to sections: one broom for each section, except that 91 has two brooms assigned to it. The manual sweeping and the litter patrol is usually carried out by the two loaders of the collection trucks when the trucks are on their way to disperse the collected refuse.

In addition to refuse collection and street sweeping, the Department of Sanitation provides the following services: (a) Flushing, (b) Lot Cleaning, (c) Abandoned Car Removal, (d) Code Enforcement, (e) Snow Removal, and (f) Equipment Maintenance. Items (c) and (d) are especially relevant to street cleaning.

Abandoned cars are usually parked illegally and thus impede curb sweeping. As soon as the presence of an abandoned car is monitored either by the district force or by residents who phone in information, a sanitation officer identifies the car, enters it in the record, and labels it with a distinctive sticker. A private company is then notified and is instructed to remove the car within three days. A final check is made to ascertain that the removal was effected. The task requires substantial effort for two reasons: (a) There are approximately 150 abandoned cars per month in the district; identification is often difficult because of out of state license plates, and (b) the efficiency and effectiveness of the operation is continuously monitored by the residents who can see how long it takes from the time the presence of the car is established until its removal.

The second activity, a very important one in this study, is the authority of officers to issue summonses for illegal curbside parking as it relates to street cleaning, and for health code and administrative violations. Since summonses for the latter must be given to the violators in person, they are rarely issued. The issuing of summonses is one of the variables that can be manipulated to improve the efficiency of the street cleaning operation.

ANALYSIS OF NO-PARKING REGULATIONS

The detailed information stored in the data bank was used to analyze the distribution of no-parking regulations and the corresponding broom assignments. The results are presented in the form of tables which show correlations between no-parking regulations, curb length to be swept, number of spaces made unavailable for parking, and work loads.

The following glossary explains the entries to be found in the tables.

1. Parking regulations
    a. Metered: Metered zone; no parking allowed between 8-9 A.M. Monday through Saturday.
    b. Day A.M.: No parking 8-11 A.M. on the indicated day.
    c. Day P.M.: No parking 11 A.M. to 2 P.M. on the indicated day.
    d. Daily: Monday through Saturday.
    e. Authorized: No parking except by Authorized Vehicles. No time period associated with this regulation.
2. Lengths
    a. Total Blockside Length: Sum of curb lengths of all blocksides having a common property, such as same parking regulation, or belonging to the same section.
    b. Effective Parking Length: The difference between total curb length and illegal parking length.
3. Available Hours: Number of hours during which the sweepers can sweep curbs with a given parking regulation. It should be noted that because of the assignment of all the sweepers to the metered zones from 8-9 A.M., the 8-11 A.M. regulation is effectively reduced to 9-11 A.M.; there are only two available hours to carry out the Day A.M. ASP assignment,

while there are three hours for the Day P.M. 11 A.M. - 2 P.M. ASP assignment.

A description of the results presented in each table is given below:

Table 4. DISTRICT 9 CURB LENGTH STATISTICS

Section	Total Blockside Length(ft)	Illegal Parking Length(ft)	Effective Parking Length(ft)	Parking Spaces
91	87588	23213	64375	2562
92	68873	16002	52871	2137
93	87959	21193	66766	2731
94	92629	14148	78481	3208
95	96930	18784	78146	3161
Harlem R. Dr. (4 slides)	48400	48400	0	0
Hudson Pkwy. (4 slides)	51600	51600	0	0
Ft. Tryon Pk.	10916	10916	0	0
Broadway Mall	2160	2160	0	0
Totals	547,055 103.6 mi.	206,416 39.1 mi.	340,639 64.5 mi.	13,799

Table 4 District 9 Curb Length Statistics

The total blockside curb length, the illegal parking length, the effective parking length and the number of street parking spaces available for each of the five sections of district nine are given. The five sections do not have equal curb lengths; the total length ranges from 68,873 ft. (section 92) to 96,930 ft. (section 95). Furthermore, the ratio of illegal parking length to effective parking length ranges from approximately 1 : 3 (sections 91, 92, 93) to 1 : 5 (section 94) with 1 : 4 for section 95. The table includes the curb lengths of the Harlem River Drive, the Henry Hudson Parkway from 155th Street North to the Henry Hudson Bridge (four sides are counted because these highways are divided), the driveways of Fort Tryon Park, and the mall of

Broadway. The total curb mileage of District 9 is 103.6 miles; however, due to the inclusion of the two highways and the park, where no parking is allowed at any time, only 64.5 miles are available for parking, approximately 65% of the total length. The maximum number of legal parking spaces is 13,799.

Table 5. DAILY SWEEPING SUMMARY

Day	Curb to be swept(ft)	% curb	Spaces per day	% Spaces
M	235,866	42.8	7333	52.8
T	252,256	45.9	8248	59.5
W	170,329	31.1	3406	24.5
Th	233,331	42.4	7399	53.3
F	254,791	46.3	8182	59.0
Sa	170,994	31.1	3472	25.0
Auth.	20,840	3.8	—	
Totals	1,338,407	243.4	—	—

Table 5. Daily Sweeping Summary

This table contains two summaries. The first one (2nd and 3rd columns) shows the curb length scheduled to be swept each day. The assignments on Monday, Tuesday, Thursday, and Friday are approximately equal at 44% of the total district curb length. The smaller values on Wednesday and Saturday reflect the fact that no P.M. sweeping is scheduled. The final entry (totals) shows that the total length scheduled to be swept in one week is 2.4 times the total curb length of the district. If the sweeping assignments were uniformly distributed, then every block-side would be swept 2.4 times per week. In practice, however, block-side curbs may be swept from once a week (highways) up to six times a week (metered zones).

The total number of legal parking spaces along street curbs is 13,799. Each no-parking regulation makes a certain number of them unavailable during a given day and time period. The second summary (4th and 5th columns) shows the total number of spaces that become unavailable for each day. It becomes immediately apparent that during Monday, Tuesday, Thursday, and Friday, parking is difficult in the district when up to 60% of the spaces become unavailable during the course of the day, while the worst days for parking are Wednesday and Saturday. Inequities become apparent when the results are broken down not only by day but also by time period.

Table 6. Sweeping Statistics by Day and Period

This table also contains two summaries. In the first one (left) the total curb length under no-parking regulations, i.e., the curb length to be swept, for each day and time period is shown. Except for Wednesday and Saturday P.M., the percentage of the total curb length to be swept during each period ranges from 13.3% to 17.7%. Since the number of available hours for each time period varies from one (metered) to two (A.M.) to three (P.M.) hours, the curb length to be swept per available hour ranges from a high of 75,243 ft. (metered, 8-9 A.M.) to 23,830 ft. (Thursday 11-2 P.M.). The Wednesday and Saturday P.M. periods reflect sweeping assignments in Section 91 only and, therefore, a comparison between these periods and all others is not valid. It should be noted that "No Parking Anytime" and "No Parking 7 A.M. to 4 P.M. on School Days" zones have been counted as having the prevailing ASP regulation in the section they occur.
The last two columns indicate clearly the inequity in the temporal distribution of the legal parking spaces: between 8 and 9 A.M. when both metered zones must be free of parked cars and the A.M. ASP regulations are in force, 34% of the spaces must be vacated. The actual proportion ranges from a low of 22% on Wednesday and Saturday to a high of 41% during Tuesday and Friday. These results can be analyzed by asking the following question: at any instant of time what is the relative probability for a driver of finding a parking space? Clearly, his best chance is from 11 to 2 P.M. and his worst from 8 to 9 A.M.

Table 6. SWEEPING STATISTICS BY DAY AND PERIOD

No parking regulation		Total curb length (ft.)	% of curb	Curb to be swept per av. hour	No. of spaces	% Total spaces
Day	Time					
Daily	8-9 AM	75243	13.7	75243	2507	18.1
Mon	8-11 AM	87343	15.8	43672	2758	19.9
Mon	11-2 PM	73280	13.3	24427	2068	14.8
Tues	8-11 AM	96569	17.6	48285	3210	23.2
Tues	11-2 PM	80444	14.6	26815	2531	18.2
Wed	8-11 AM	78344	14.3	39172	499	3.6
Wed	11-2 PM	16742	3.0	5581	400	2.8
Thurs	8-11 AM	86599	15.7	43300	2759	19.9
Thurs	11-2 PM	71489	13.0	23830	2133	15.3
Fri	8-11 AM	97313	17.7	48657	3209	23.2
Fri	11-2 PM	82235	14.9	27412	2466	17.7
Sat	8-11 AM	80800	14.7	38800	500	3.6
Sat	11-2 PM	14951	2.7	4984	465	3.3
Authorized		20840	3.8		716	5.1

Note: Daily totals include the following special blocksides

Henry Hudson Parkway,	4 sides, Sat. AM
Harlem River Drive,	4 sides, Wed. AM
Fort Tryon Park,	2 sides, Wed. AM, Sat. AM
Broadway Mall,	2 sides, Wed. AM, Sat. AM

Further analysis of the curb length to be swept for each parking regulation shows that sweeping assignments for Monday, Tuesday, Thursday, and Friday are approximately equivalent in each section as measured by the ratio of daily sweeping assignment to total curb length of the section. These ratios range from 0.503 to 0.642 with an average of 56.3%. The totals, however, which indicate how often on the average a curb is swept in a section per week range from 2.34 times (section 95) to 3.32 times (section 91). The reason for this discrepancy becomes apparent if the length of the metered zones is compared. These range from 24,971 ft. in section 93 to 9,214 ft. in section 95, with 16,053 ft. in section 91. Since metered zones are swept daily, districts with many meters show that on the average curbs are swept more often. This is misleading, because most non-metered zones (not in section 91) are scheduled to be swept twice a week.

If curb length to be swept per available hour is considered for each parking regulation in each section, the following observations are made:

In sections 91 and 92 there is almost a factor of 2 to 1 between the length to be swept per hour of AM ASP regulation and of PM ASP regulation. Furthermore, the metered length which should be swept from 8 to 9 A.M. (one hour) is approximately equal to the length with A.M. ASP regulation that should be swept from 9 to 11 A.M. (two hours). In sections 94 and 95 the curb length per hour for the metered and the A.M. ASP regulation zones is comparable, but twice that of the P.M. ASP regulation. In section 93, 24,971 ft. of metered curb length is scheduled to be swept in one hour; the length per available hour during the Alternate Side Parking regulation ranges from only 951 ft. to 9,630 ft. These results clearly indicate inequities in the distribution of curb length to be swept per available hour. Such inequity was apparent when the whole district was analyzed, but becomes more pronounced when section assignments are scrutinized. If averages are considered, then 15,050 ft. of metered curb length must be swept in one hour while only 5,767 ft. per hour must be swept during 9 A.M. to 2 P.M. when ASP regulations are in force.

Finally, a section by section analysis of the number of spaces to be vacated during the various parking regulations shows that the daily availability of parking spaces is not distributed uniformly in the five sections. For example, in section 91, the distribution is uniform for every day and time period, while in section 94 the number of spaces that must be vacated varies from 270 on Monday and Thursday 11-2 P.M. to 1,225 on Tuesday and Friday 8-11 A.M. Such non-uniformity creates dissension in the community because it creates the impression that some sections receive preferential treatment.

It is clear that the 14,000 legal curbside parking spaces are too few to accommodate the number of cars in a district of this size (300 blocks) and population (200,000) with very limited off-street parking facilities. The result is inadequate compliance to no-parking regulations, or, when the ASP regulations are enforced, the appearance of widespread double parking. Any long range effort in improving the street cleaning operation should include provisions for the eventual decrease of the number of cars that must be parked in the streets.

The increase over the years in the number of metered spaces has increased the length of curb that must be swept from 8 to 9 A.M.; it is 75,243 ft. or 13.7% of the total. It is, in general, twice the length scheduled to be swept than in any other one hour period. This fact leads to the conclusion that it is unrealistic to expect the brooms to sweep all the metered zones and proceed to Alternate Side of the Street parking zones before 9 A.M. Therefore,

1. There is no need to ban parking in all ASP zones prior to 9 A.M.
2. It may be necessary to extend the amount of time available for sweeping metered zones from one to one hour and a half, preferably from 7:30 to 9:00 A.M.

With the increase in metered zones the inequity between A.M. and P.M. ASP regulations has become more pronounced. It is clear that a three hour period is not necessary for carrying out the sweeping scheduled for the period 11-2. Therefore,

3. The 11 A.M. to 2 P.M. ASP regulation should be modified by reducing the time period from three to two hours.

If it is recognized that the current practice, in accordance with Departmental regulations, is that the lunch break occurs between 11:00 and 11:30 A.M. and, furthermore, that time for the return trip to the 215th Street facility must be provided for in the scheduling, then the recommended time period for the afternoon assignment is 11:00 A.M. to 1:00 P.M. The implication is that in conjunction with recommendation #2 the lunch break will be scheduled from 10:30 to 11:00 A.M.

The preceding analysis indicates that because of the lack of adequate parking facilities, the non-compliance to the parking regulations is high. The results of the study to determine enforcement policies that will reduce the number of illegally parked cars is presented in the next two sections, VI and VII.

SECTION VI

THE EFFECT OF ILLEGALLY PARKED CARS

Curbs should be free of illegally parked cars, if sweeping by mechanical brooms is to be effective. However, the lack of an adequate number of legal parking spaces at the curb or off-street and the various difficulties associated with enforcement of the no-parking regulations have resulted in widespread noncompliance. Consequently, the operators of the sweepers are forced to maneuver around illegally parked cars and miss a substantial portion of the curb. Thus, the effectiveness of the cleaning operation is sharply reduced. In this section, the relationship between compliance to the regulations and curb length that can be swept is analyzed.

Intuitively, the length of curb swept is a function of various parameters. These may be classified as machine-operator parameters and environmental ones. Those in the first group may include sweeper maneuverability and the operator's proficiency, while those in the second may include compliance to parking regulations, the distribution of illegally parked cars, the weather, etc. In order to determine the effect of these parameters on the length of curb swept, it was necessary to develop an explicit mathematical model. The lack of any previous research in this area necessitated the development of the required relationships from fundamental considerations.

MODEL PARAMETERS

The effects of machine-operator parameters on length of curb that can be swept are examined first. A key quantity in this analysis is the total clearance required by a sweeper to maneuver around one illegally parked car. This variable, denoted by TC, is a measure of the maneuverability of the sweeper and the skill of the operator. Expressed as the sum of the front and rear clearances (see Figure 2D), TC is also a measure of the curb missed for each car bypassed. Furthermore, for more than one car, the total missed curb is the sum of the clearance distances for each car plus the lengths of the cars (Figure 2D) provided the cars are sufficiently far apart.

Another important machine-operator parameter is intercar distance. The effect of intercar distance on swept curb length is determined by assuming first that two cars are illegally parked bumper to bumper. The amount of curb side missed by a sweeper bypassing the cars will be $L_1 + L_2 + FC + RC$, where L_1 and L_2 are the lengths of cars 1 and 2, and FC and RC are the front and rear clearances, respectively (Figure 2A). As the distance between the cars increases, the amount of unswept curb also increases in proportion to the intercar distance (Figure 2B). At some critical distance, M_0, the sweeper will begin to maneuver between the two cars (Figure 2C). From this point on, the unswept distance decreases as the sweeper is capable of maneuvering more and more efficiently. Finally, when the cars are sufficiently far apart to be considered independently, the unswept distance will level off to a constant value $L_1 + L_2 + 2FC + 2RC$ (Figure 2D).

For a block of length L, the amount of street swept is L minus the unswept distance. The resulting relationship between curblength swept, YF, and intercar distance, DI, is shown in Figure 3, where ε is the additional distance necessary for the cars to be considered independently.

The critical intercar distance, M_0, is ideally equal to the total clearance (Figure 2C); however, the minimum distance for which the sweeper can maneuver between two cars depends upon the skill of the operator. Moreover, by definition, the total clearance cannot be greater than the critical intercar distance.

In considering the environmental parameters, emphasis is placed on the compliance to parking regulations. As the number of illegally parked cars increases, the amount of curb side accessible to the sweeper decreases. Therefore, the amount of curb that can be swept also decreases. Furthermore, the density of illegally parked cars has a limiting effect on the maneuverability of the sweeper, which results in an additional

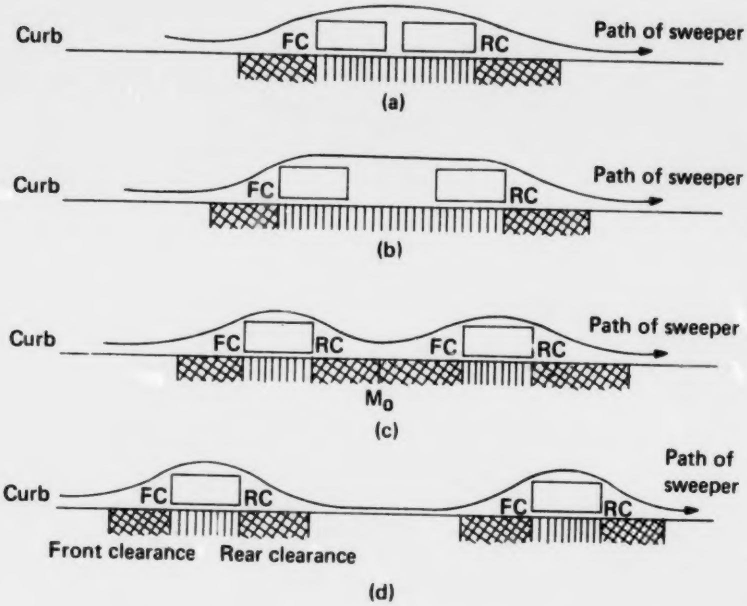

Curb
FC
RC
Path of sweeper
(a)
Curb
FC
RC
Path of sweeper
(b)
Curb
FC
RC
FC
RC
Path of sweeper
M0
(c)
Curb
FC
RC
FC
RC
Path of sweeper
Front clearance
Rear clearance
(d)

Fig. 2 The effect of machine-operator parameters on curblength swept. (Shaded area = unswept curb.)

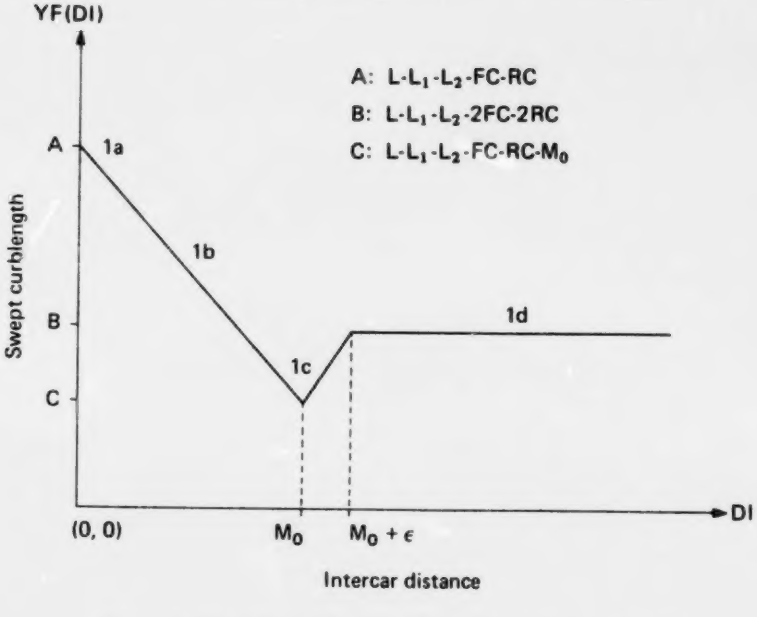


Fig. 3 The effect of intercar distance on swept curblength.

decrease in curb length which is swept. The last parameter considered is the distribution of illegally parked cars. For a fixed number of cars, the location of each on the block, and the position of each with respect to the others, has an effect on the curb length swept.

METERED PARKING

The Mathematical Model

Metered parking zones were used first to study the effects of the various parameters on the expected length of curb that can be swept. This choice facilitated the mathematical modeling and the computation of the expected values of swept curb. By considering each space as a discrete entity, the swept distance was determined by simple summation (this will become clearer in the sequel). To simplify further the development of this relationship, it was initially assumed that the sweeper could maneuver between two cars as long as the intercar distance was at least as great as one metered space ($M_0 \leq 1$). Furthermore, whenever two or more cars were parked in tandem, bumper to bumper, the missed curb was just the sum of the lengths of the cars plus the front clearance of the first car and the rear clearance of the last car (Figure 2A).

Expressing the variables FC and RC as fractions of a metered parking space, the actual curb length that could be swept was tabulated for a block with N consecutive spaces as the number of illegally parked cars, I, varied from zero to N. (A summary of symbols is given in Table 7.) These numbers represented the sum of the empty spaces minus the appropriate sums of front and rear clearances. For each value of I, the expected (average) length of curb swept, $\overline{Y}$, expressed in metered space units, was computed using the formula

$$\text{Average curblength swept} = \sum_{i=1}^{{}_N C_I} P_i \times (\text{curblength swept})_i \qquad (1)$$

where ${}_N C_I$ represents all the possible sets of I occupied, distinguishable

Table 7. SUMMARY OF SYMBOLS

Symbols	Definition
N	number of available spaces on a block
I	number of illegally parked cars on a block
FC	front clearance in bypassing a parked car
RC	rear clearance in bypassing a parked car
TC	total clearance, FC + RC
S	per cent of curb (block) swept
C	compliance to parking regulations
$\overline{C}$	noncompliance, 1 - C
L	total length of a block (in feet)
L_i	length of car i (in feet)
DI	intercar distance
D	intercar distance expressed in units of a metered space
M_0	critical (minimum) intercar distance for which a sweeper maneuvers between two cars
ϵ	the additional distance necessary for two cars to be considered independently
Y	swept curblength expressed in units of a metered space
YF	swept curblength expressed in feet
UYF	unswept curblength expressed in feet
LE	effective length of a block, $L - \sum_{i=1}^{I} L_i$

parking spaces on a block of size N without regard to the identity of the cars parked in those spaces, i.e., it is the collection of sets into which I elements may be grouped from N choices without regard to the order of arrangement within the group[9]. Furthermore, P_i is the probability of the ith set. If all the metered spaces are initially assumed occupied and have to be vacated at the time of the parking regulation, each arrangement resulting from (N - I) cars leaving metered spaces at random is equally likely with probability $1/{}_NC_I$.

The resulting expression for the expected length of curb that can be swept, in units of metered spaces, is given by Equation 2

$$E(Y) = \frac{N - I}{N} (N - I \cdot TC) \qquad (2)$$

where TC is the total clearance expressed as a fraction of a metered space.

Since the number of empty parking spaces is the difference between the number of available spaces, N, and the number of illegally parked cars, I, the compliance to parking regulations can be expressed as:

$$C = \text{Compliance} = \frac{N - I}{N} \; ; \qquad (3)$$

in similar fashion, noncompliance is written as:

$$\overline{C} = \text{Noncompliance} = 1 - C = \frac{I}{N} \; . \qquad (4)$$

Substituting Equations 3 and 4 into Equation 2, dividing the result by the number of available spaces and multiplying by one hundred yields the following relationship between percentage swept and compliance:

$$S = 100 \times [(TC)C^2 + (1 - TC)C] \quad 0 < M_0 \leq 1 . \qquad (5)$$

Although Equation 5 exhibits the quadratic nature of the relationship between S and C, it is Equation 2 that leads to a natural interpretation.

The expected curblength that can be swept given N spaces and I illegally parked cars is proportional to the total length adjusted for the clearance required to maneuver around each illegally parked car. The constant of proportionality is, naturally, the compliance. Note, that for perfect maneuverability, TC = 0, the average curb swept is simply

$$E(Y) = N \cdot C \, .$$

The preceding development is valid for $0 < M_0 \leq 1$, where the value of

M_0 is expressed in metered space units. Now let $1 < M_0 \leq 2$. Since metered parking is assumed, values of M_0 in this range imply that the sweeper is unable to maneuver between two cars separated by a distance of less than two spaces. Therefore, the expected curblength swept between pairs of cars with such a separation is zero.

The average length of curb swept is the same for $0 \leq M_0 \leq 1$ and $1 < M_0 \leq 2$ when the number of illegally parked cars is zero or one. When I is greater than one, the two values are different with the one for $1 < M_0 \leq 2$ less than the one for $0 \leq M_0 \leq 1$. The discrepancy appears because every time the configuration of two cars separated by one space occurs, there is a contribution of (1 - TC) units of swept length to the calculation of the average for $0 \leq M_0 \leq 1$, while the contribution is zero for $1 < M_0 \leq 2$.

For I illegally parked cars on a block with N spaces, the number of possible arrangements with a distance D between two cars in tandem is given by

$${}_{N - 1 - D}C_{I - 1}$$

where N - I - D reflects the reduction in the number of spaces than can be occupied and the term I - 1 results from considering the j^{th} and $(j + 1)^{st}$ car and the distance between them as one entity. The probability for one such event to occur is given by

$$\frac{{}_{N - 1 - D}C_{I - 1}}{{}_{N}C_{I}}$$

Finally, for I cars, there are exactly I - 1 intercar distances, each of which may have length varying from zero to N - I. Therefore, the expected value of the discrepancy is given by

$$(1 - TC)\left[\frac{{}_{N - 1 - D}C_{I - 1}}{{}_{N}C_{I}}\right](I - 1)$$

For the case $1 < M_0 \leq 2$, D = 1, the above expression reduces then to

$$(1 - TC)\left[\frac{I(N - I)}{N(N - 1)}\right](I - 1) \qquad (6)$$

By subtracting Equation 6 from Equation 2 and collecting terms, the average length of curb swept is obtained

$$E(Y) = \frac{N - I}{N} \left[N - \frac{I(I - 1)}{N - 1} - TC \frac{I(N - I)}{N - 1} \right] \qquad (7)$$

Using the relationships for compliance and noncompliance (Equations 3 and 4), after much algebraic manipulation a relationship between per cent swept and per cent compliance is obtained:

$$S = 100 \times \left[C^2 \left[\frac{N(2 - TC) - 1}{N - 1} \right] - NC^3 \left[\frac{1 - TC}{N - 1} \right] \right] = 100 \times [E(Y/N)] \qquad (8)$$

Proceeding as above, the expression for expected curblength swept can be generalized.

For $A < M_0 \leq B$, where A and B are the largest and smallest integers bounding M_0, respectively, the expected value of curblength swept is given by

$$E(Y) = \frac{N - I}{N} (N - I \cdot TC) - \sum_{D=1}^{A} (D - TC) \left[\frac{N - 1 - D^{C}I - 1}{N^{C}I} \right] (I - 1) \qquad (9)$$

RESULTS

With the relationships derived in the previous section, it is now possible to examine the effects of the various parameters on the amount of street swept. First, the linear dependence of the per cent of street swept, S, on the total clearance, TC, is shown in Figure 4 for a realistic value of intercar distance (M_0 is equal to two parking spaces). The plot drawn for N = 10 and N = 20, demonstrates that the relationship is virtually independent of the size of the block. In addition, it shows that the slopes of these curves are also a function of the compliance.

In Figure 5, the relationship between curb swept and compliance to parking regulations is plotted for various values of total clearance with $M_0 = 2$. As the total clearance increases, the compliance needed to achieve a desired level of sweeping also increases. In addition,

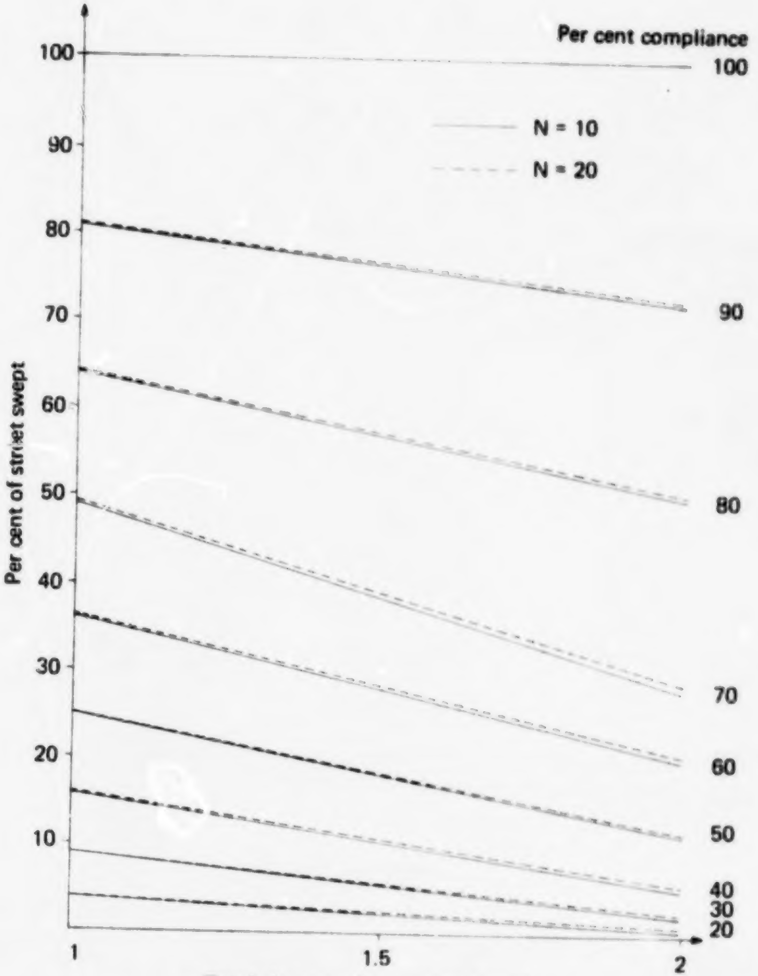


Fig. 4 Per cent of street swept versus total clearance (M_0 = two spaces.)

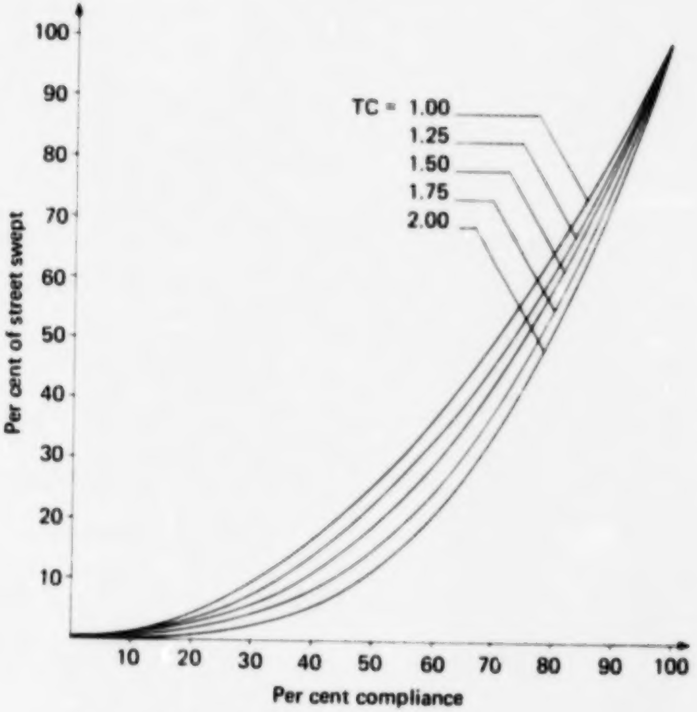


Fig. 5 Per cent of street swept versus per cent compliance. (Metered Parking; M_0 = two spaces, N = 10.)

the level of compliance (measured in per cent) is always greater than the per cent of street that can be swept. Furthermore, since the slope of the curves rises sharply for compliance greater than fifty per cent, the increase of per cent swept per unit rise in compliance will be greater for high compliance values.

In Figure 6, the effect of critical intercar distance is shown for blocks with ten and twenty spaces (TC = 1.25). The result is a set of piecewise linear curves with the value of each step decrease a function of compliance and the respective discrepancy. The value of the per cent swept at the discontinuities is equal to the higher value. Note that blocksize is now an important variable. For a block with twenty spaces, a given compliance implies a greater number of illegally parked cars than a ten space block with the same compliance. This, in turn, implies a greater number of intercar distances. Thus, the effect of M_0 on the $N = 20$ block will be greater than that on the $N = 10$ block for a given compliance.

Finally, per cent swept versus per cent compliance for different values of M_0 (TC = 1.25), is plotted in Figure 7 for $N = 10$. Again, the similarity of the curves indicates the slight effect the size of the block has on per cent of curb swept. For each case, as the critical intercar distance increases, the per cent of compliance needed to achieve a desired level of sweeping also increases. The insensitivity of per cent swept to changes in M_0 for high compliance results because these compliance values imply only one illegally parked car.

NON-METERED PARKING

Curbs with continuous parking zones are next used to study the effects of the various parameters on the expected length of curb that can be swept. Continuous zones imply that the cars can be situated anywhere along a prescribed section of a block. However, the exact location of a car depends on the location of all other cars on the block. An analytical model based on the conditional probability that a car be at a certain location was developed for the two car case and an exact

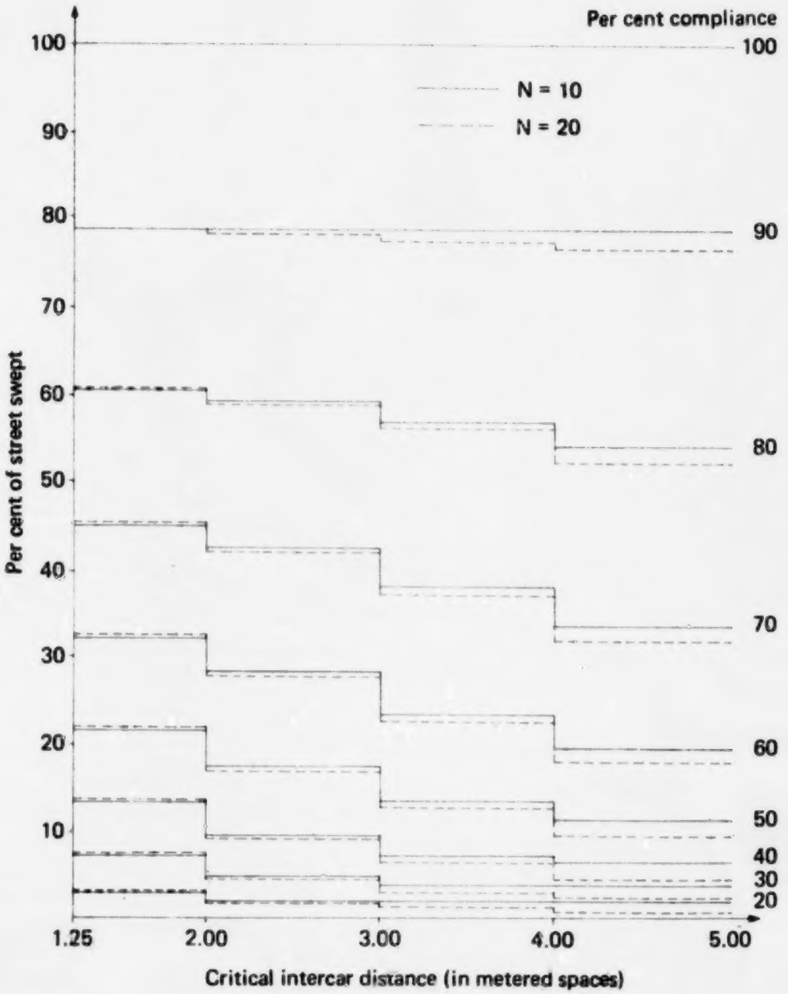


Fig. 6 Per cent of street swept versus critical intercar distance.
(TC = 1.25 spaces.)

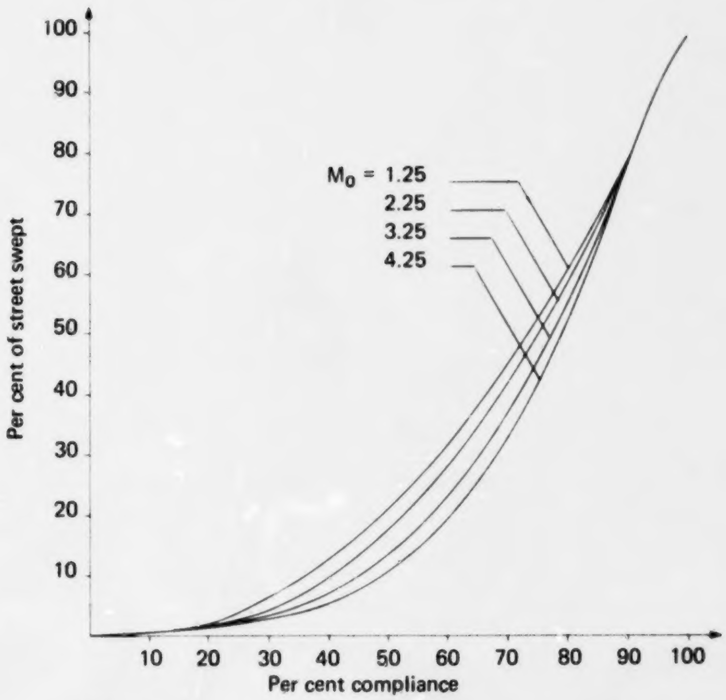


Fig. 7 Per cent of street swept versus per cent compliance.
(Metered Parking; TC = 1.25 spaces, N = 10.)

solution was obtained. This mathematical model is analogous to the one for the metered case.

Since the extension of this model to the many car case yielded unwieldy expressions for determining the expected length of curb swept, it became necessary to develop a computationally efficient algorithmic model to approximate the continuous parking case.

THE MOMENT MATCHING APPROXIMATION

In the development of the metered case the distribution described by a probability function f(x) that characterizes the relative position of I illegally parked cars on a block was assumed uniform, i.e., the probabilities of a car occupying any available space are equally likely. If, however, these distributions are interpreted as mass densities, where f(x) is a continuous function representing the "force" exerted on a block by any number of parked cars, then it is possible to determine discrete probability mass functions whose overall effect on the block is the same. This is accomplished by equating the first I moments of the continuous and the discrete distributions. Furthermore, the discrete points associated with the probability mass function (discrete) will correspond to the location of the cars on the block. In effect, this method determines the expected positions of the cars as opposed to the expected length of curb swept. With these positions, however, it is then possible to compute directly the corresponding curblength swept.

In order to locate I cars of zero length, i.e., I points, so that they are a discrete equivalent of a continuous distribution, it is necessary to determine an effective blocklength, LE, to compensate for the actual lengths of the cars L_i. This is accomplished by subtracting the length of the cars from the total length of the block, L

$$\text{Effective Blocklength} = LE = L - \sum_{i=1}^{I} L_i \qquad (10)$$

If a new variable is defined

$$v = \frac{x}{LE} \tag{11}$$

so that $0 \leq v \leq 1$ when $0 \leq x \leq LE$, then the normalized moment matching equations become

$$\int_0^1 v^k f(v)dv = \sum_{i=0}^{I} w_i v_i^k \; ; \quad k = 0, 1, 2, \ldots, I \tag{12}$$

where the v_i are the normalized unknown equivalent location of the cars. The weighting coefficients, w_i, can be interpreted as a measure of the relative size of the cars.

Equations of this form belong to the class of equations known as Gaussian Quadrature.[10] The general formula for this class is given by

$$\int_a^b h(x)g(x)dx = \sum_{i=1}^{I} w_i g(x_i) \tag{13}$$

where $h(x) > 0$ and w_i and x_i are unknown parameters.

There is a well-known method[11] for solving this particular system of nonlinear equations.

By defining a sample polynomial, $\pi(x)$, as

$$\pi(x) = \prod_{i=1}^{I} (x - x_i) = \sum_{k=0}^{I} C_k x^k = C_0 + C_1 x + C_2 x^2 + \ldots + C_I x^I \tag{14}$$

where $\pi(x_i) = 0$; $i = 1, 2, \ldots I$, and where the C_k are computed from the equations

$$\sum_{k=0}^{I} C_k m_{k+j} = 0; \quad j = 0, 1, \ldots I - 1 \tag{15}$$

it is possible to solve for the values of x_i by setting Equation (14) equal to zero.

Thus the procedure for determining the per cent of curblength swept using the moment matching model can be summarized as follows:

1. compute 2I moments of x, m_i
2. solve a system of simultaneous linear equations for C_k
3. determine the roots of an I^{th} degree polynomial
4. compare the positions of the cars ($LE - x_i$) with M_0, FC and RC to determine the unswept curblength
5. subtract unswept curblength from length of block
6. divide swept curblength by length of block for per cent swept.

A computer program was written to carry out the computations indicated above.

Using the results of the exact solution for the continuous case as reference, the moment matching approximation and the metered solution for one and two illegally parked cars were compared: both models were good approximations to the continuous case. Further comparison of the two models reveals that the moment matching approximation converges more rapidly on the exact solution than the metered one. In addition, the rate of convergence is affected by the critical intercar distance and the total clearance. It is noted, however, that for small size blocks the metered solution provides a better approximation. These cases are analogous to blocks with a high density of illegally parked cars; hence the availability of parking spaces is greatly reduced. Thus a metered solution is the logical choice.

In order to establish a criterion for selecting the best approximation, the per cent differences for the metered and moment matching cases are plotted in Figure 8 for two illegally parked cars. A study of these curves suggests that if the following inequality is satisfied then the metered solution should be used;

$$L \leq \left[\sum_{i=1}^{I} L_i + I(TC) + (I - 1)(M_0) \right] \qquad (16)$$

otherwise the moment matching approximation should be used.

In the region where this inequality holds (as an example consider L = 80 feet in Figure 8), the single biased position of the cars as found in the moment matching case gives a lower value of area swept than in the metered case where all combinations are examined.

RESULTS

By combining the criterion for selecting the best approximation with an algorithm for metered and moment-matching solutions, the effects of the various parameters on the relationship between per cent compliance and per cent swept was examined.

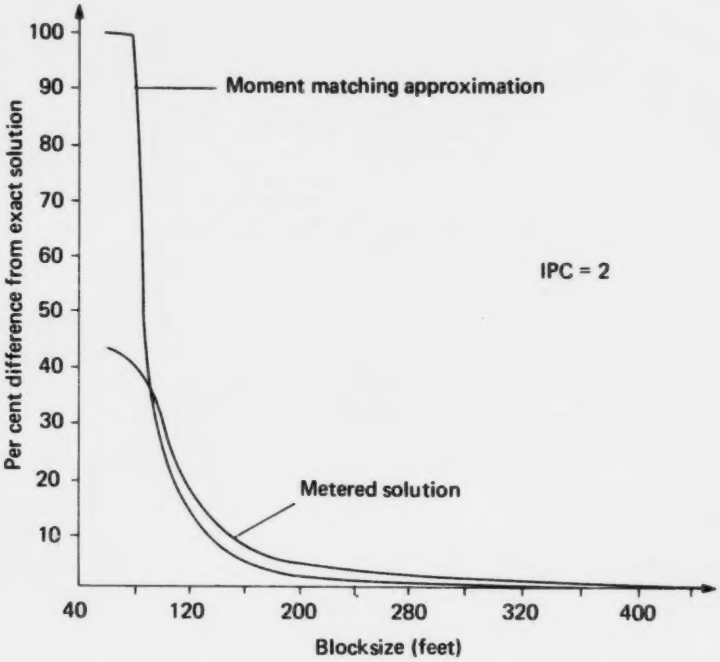


Fig. 8 Comparison of moment matching approximation with metered solution. (M_0 = 25 feet, TC = 20 feet.)

A study of the results indicates that, as in the metered case, the relationships are independent of changes in FC and RC as long as the total clearance remains the same. The dependence of the per cent of street swept on total clearance is illustrated in Figure 9. The plot, drawn for L = 200 and 400 feet, demonstrates that the relationship is independent of the size of the block. In addition, it shows that the exact slope of the curves is also a function of the compliance.

In Figure 10, the relationship between street swept and compliance for various values of total clearance is shown (M_0 = 40 ft.). As the total clearance increases, the percent compliance needed to achieve a certain level of sweeping also increases. In addition, the per cent compliance is always greater than the per cent of street that can be swept.

In Figure 11 the effect of critical intercar distance on per cent swept is shown for blocks 200 and 400 feet long. In the region where the moment matching model is used, the per cent swept for each value of compliance is constant for the range of M_0 considered, whereas when the metered-zone approximation is used the result is the expected piecewise linear curve. These constant values occur because the moment matching solution at the respective levels of compliance positions the cars far enough apart so that only very large (and impractical) critical intercar distances M_0 will affect the per cent swept. In addition, as in the metered case, block size is a parameter that cannot be neglected.

Per cent swept versus per cent compliance for various values of M_0 (TC = 25) is plotted for a block of length 200 feet in Figure 12. Once again, the dashed-line regions correspond to the changing of the models. These curves verify the conclusions of the preceding paragraph. In addition, as the critical intercar distance increases, the level of compliance needed for a given level of sweeping also increases.

Finally, the effect of different probability density functions for the distribution of the illegally parked cars was examined. Two triangular PDF's are considered, one corresponding to the assumption that the parked cars tend to bunch up in the middle of the block (peak at 0.5, $f(x) = \Delta$) and the other that the cars tend to park at one end of the

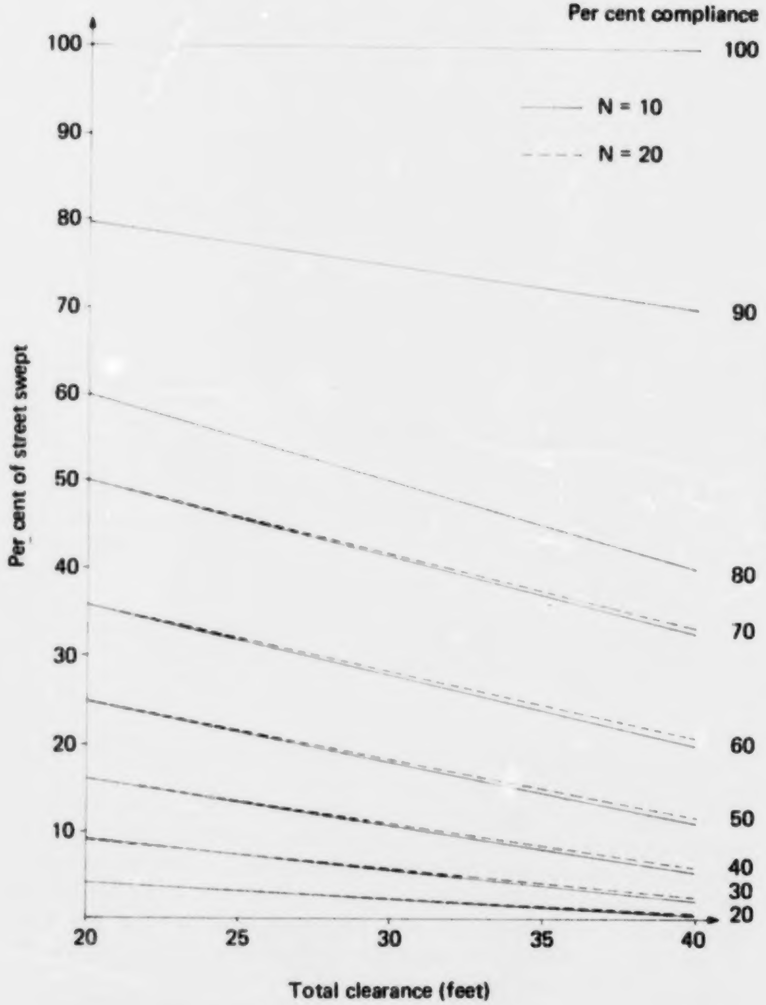


Fig. 9 Per cent of street swept versus total Clearance. (M_0 = 40 feet.)

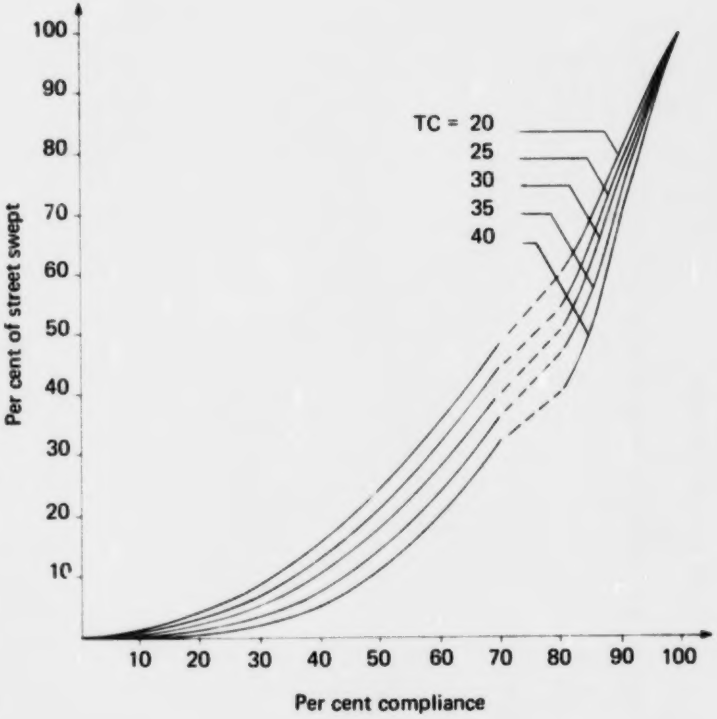


Fig. 10 Per cent of street swept versus per cent compliance. (Non-metered Parking, M_0 = 40 feet, N = 10.)

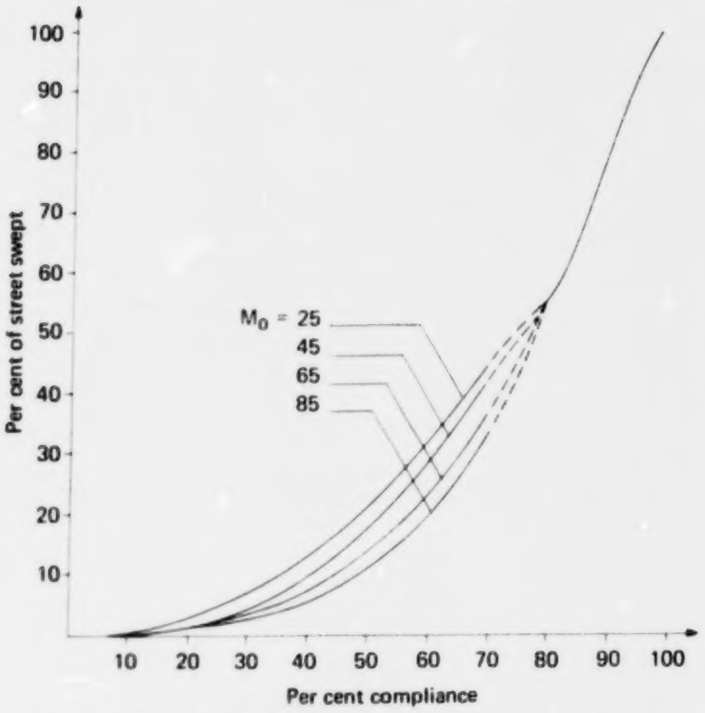


Fig. 12 Per cent of street swept versus per cent compliance. (Non-metered Parking; TC = 25 feet, N = 10.)

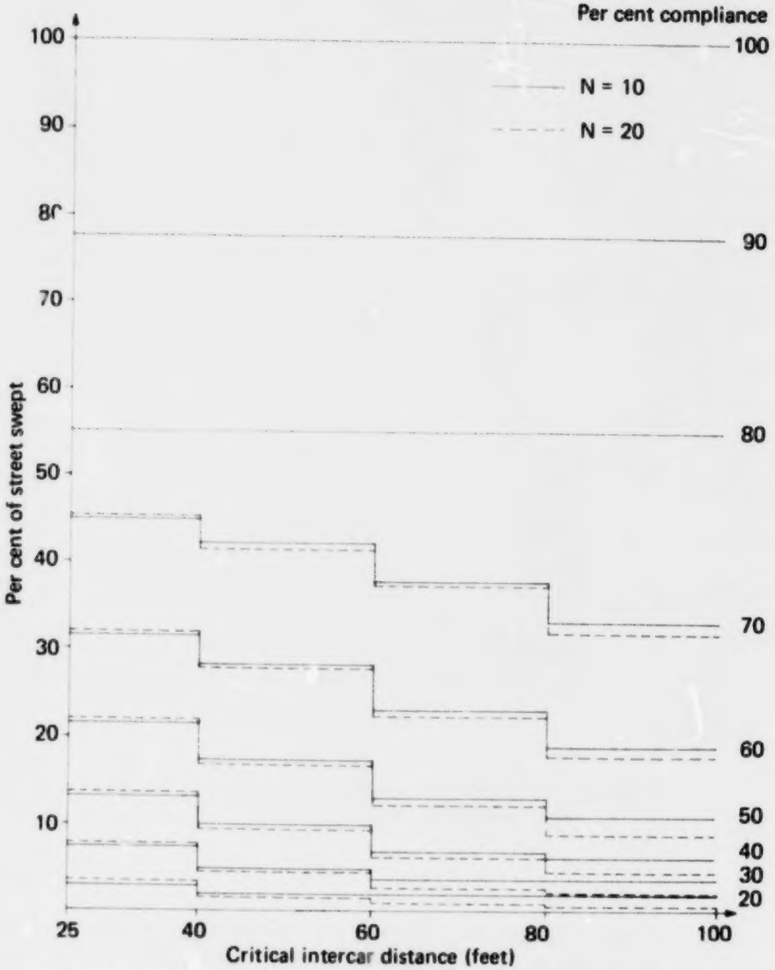


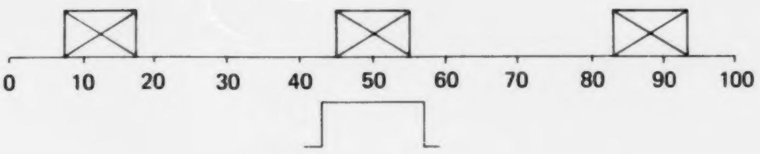
Fig. 11 Per cent of street swept versus critical intercar distance. (TC = 25 feet.)

block (peak at 1, $f(x) = \Delta$). A study of the results indicated that the different PDF's had little effect on the per cent of street swept. This can be explained by looking at the positions of three cars on a 200 foot block for the various distributions considered (Figure 13). The shifting of the positions for each distribution is small enough so that the model will have transferred to the metered solution before any deviation due to position changes occurs. Thus, the two-region model of the continuous parking case is insensitive to the distribution of illegally parked cars assumed. Note that the last distribution is non-symmetric and that the resulting equivalent lengths of the cars vary.

CONCLUSIONS

The results that have been presented demonstrate unequivocally the well known dependence of street cleaning by mechanical brooms on the compliance to parking regulations. For the first time, a simple analytical model was constructed that permits the quantitative evaluation of the degradation of performance due to illegally parked cars on both metered and non-metered streets. These results are virtually independent of the length of the block. Even in the unrealistic case of perfect maneuverability, i.e., no clearances are necessary, a compliance higher than 30 per cent is required for more than 15 per cent of the curb to be swept (on the average). For realistic sweeper maneuverability, 50 per cent compliance yields at best 25 per cent of curb swept. Since for a street to be clean at least 70-80 per cent of the curb must be swept (if not more in areas of high litter generation), the compliance to parking regulations must be kept at 85 per cent or higher. Enforcement policies for accomplishing that are presented in the next section.

These results also demonstrate the rapid degradation in street cleaning performance if the maneuverability of a machine is impaired or if the driver is not skilled. The effect of an unskilled or inattentive operator would be to decrease the curblength swept for a given level of compliance. Hence, the best results are obtained by skilled drivers intent on utilizing the machine's maneuverability to advantage.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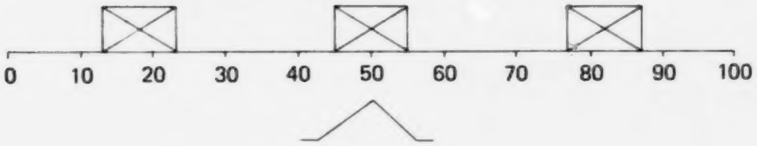
(a) Uniform distribution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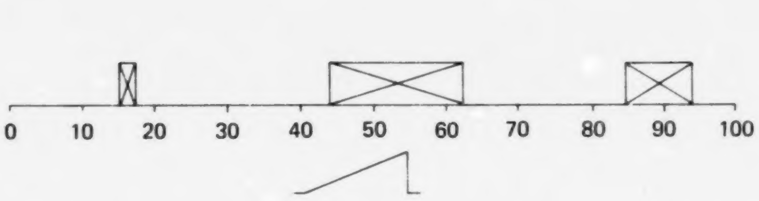
(b) Triangular distribution

(peak at .5)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(c) Triangular distribution

(peak at 1.)

Fig. 13 Effect of various distributions on the positions of illegally parked cars. (N = 10, I = 3.)

SECTION VII

ENFORCEMENT POLICIES FOR PARKING REGULATIONS

In the previous section analytical models were presented that related the length of curb that could be swept to the number and distribution of illegally parked cars. It was shown that high compliance levels (85%) are necessary to sweep 70-75% of a curb. The lack of adequate free or low cost parking facilities makes voluntary compliance unlikely, thus necessitating active enforcement of the no-parking regulations. Enforcement, generally in the form of the issuance of summonses, is carried out by several different agencies of the city government, such as the Police, Sanitation, Fire and Traffic Departments. This section is focused on the effect that different enforcement policies have on the level of compliance. Only the practices of municipal personnel whose primary responsibility is the enforcement of parking regulations are considered. The Meter Maids of the Traffic Department and the enforcement officers of the Sanitation Department are two such groups in New York City.

As shown in Section V the most prevalent parking regulations in urban areas are No Parking Anytime, Alternate Side-of-Street Parking (ASP), metered zone restrictions, and No Parking Except Authorized Vehicles (e.g., taxis, delivery trucks, governmental vehicles, etc.). These regulations are generally enforced by officers whose daily assignments are determined on an ad-hoc basis. Their enforcement schedules are based mainly on reports of low compliance by sanitation foremen and sweeper operators, and on complaints about parking violations and unswept streets from the community. However, by the time an officer is actually assigned to an area, the conditions which prompted the assignment may have changed. Since the officer is instructed to remain within the area, a misallocation of manpower results. If the effects of a particular enforcement schedule could be evaluated in terms of a predicted level of compliance, alternative schedules could be selected and greater flexibility in assignments could then be possible. Thus, the development of a systematic procedure for determining enforcement policies that take into account the dynamic response of the system is warranted. In this section a mathematical model relating compliance to enforcement is presented and a procedure for designing routes for enforcement officers is proposed.

MODEL SELECTION

The two experimentally measurable quantities are the number of illegally parked cars and the number of tickets issued on each blockside. Since, in general, all violators are issued summonses when enforcement takes place, it is sufficient to record only the number of cars and whether the regulations were enforced. Specifically, enforcement on the i-th day is denoted by u_i, where $u_i = 1$ if ticketing occurred, and $u_i = 0$ if no tickets were issued. The original data are converted into a quantity that is independent of the length of the block by defining compliance to parking regulations on the i-th day as

$$c_i = 100 \times \frac{N-I}{N} \tag{17}$$

where N is the total number of parking spaces on a blockside and I is the number of illegally parked cars. Parking spaces may be clearly defined discrete entities, as in metered zones, or continuous, as in non-metered areas.

Data indicating the dependence of compliance to enforcement were collected daily for a period of five months by residents[12] of Sanitation District 9. The data, shown in Figure 14, were taken in a metered zone (No Parking from 8 to 9 A.M.). The experimental procedure consisted of counting the number of illegally parked cars at the time summonses were issued. For days when no enforcement took place, data were collected 15 to 20 minutes before the expiration of the no-parking regulation.

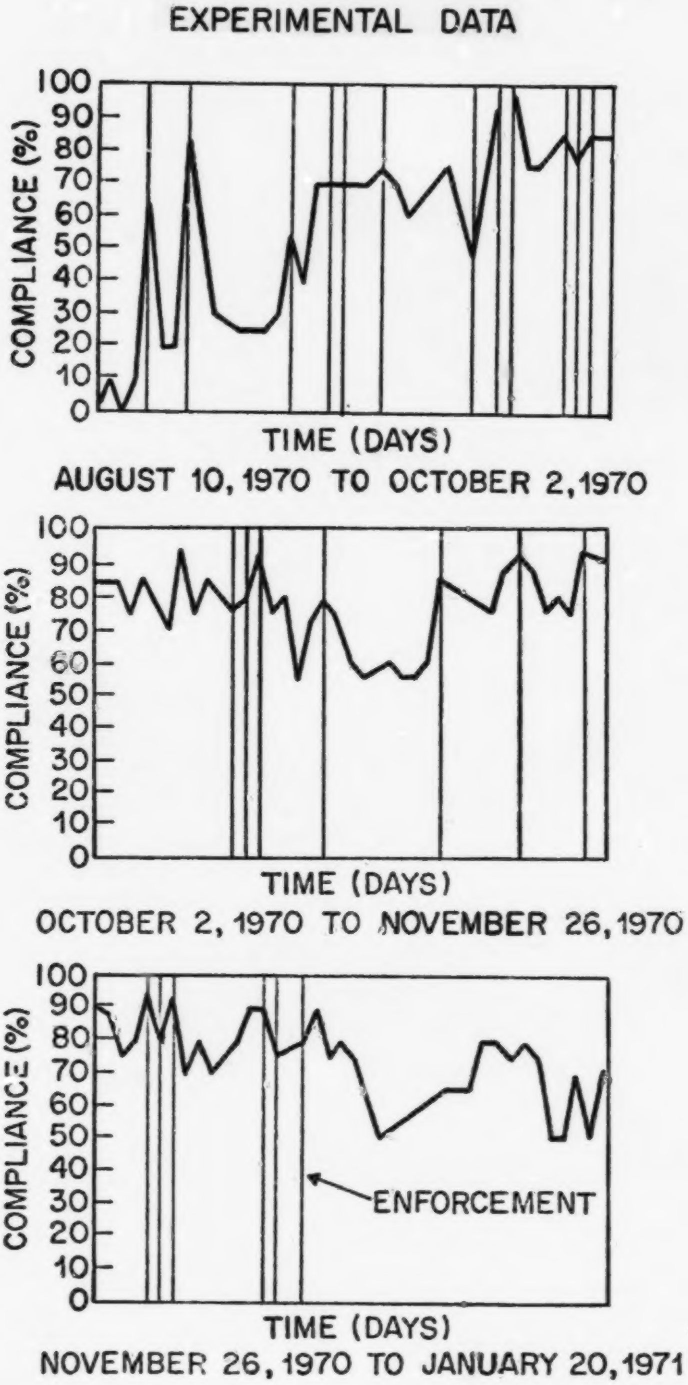

Fig. 14 Daily experimental data for compliance and enforcement.

It should be noted that data for a nonmetered area with the same enforcement schedule might be quite different. The experimental zone consisted of three blocksides on each side of a two-way street with retail commercial establishments. It was observed that on several occasions (see Fig. 14) compliance increased at the very time enforcement took place. This indicated that many of the illegally parked cars belonged to store owners or customers who, realizing that enforcement was to take place (e.g. an officer issuing summonses on the next block), moved their cars. In high density residential areas with nonmetered parking regulations, however, the decision to park illegally is made the night before; during the day people are either at work or cannot monitor the street continuously. Therefore, enforcement does not have an immediate effect on compliance as is the case for commercial-metered zones.

Analysis of the data indicated that compliance during any time period is not only a function of the current enforcement, but also of the previous history. Several dynamical system models were tried, but the results were not satisfactory. For example, a first order linear difference equation model relating enforcement to compliance with parameters estimated using a mean square error criterion proved unsuccessful: simulation results did not exhibit some of the characteristic features of compliance behavior such as anticipation of enforcement. It became apparent that a stochastic model was necessary; a finite state machine one was selected because it eliminated the need for state constraints and offered flexibility in the choice of states.

Let x be the state, u the input, and y the output. The enforcement on the i-th day, u_i, can take one of the two values, zero or one, as described earlier. The output y_i takes the value of zero if the compliance level on the i-th day is less than or equal to a threshold value α, and the value of 1 if the compliance is larger than α, as shown in Figure 15.

$$y_i = \begin{cases} 0 & c_i \leq \alpha \\ 1 & c_i > \alpha \end{cases} \tag{18}$$

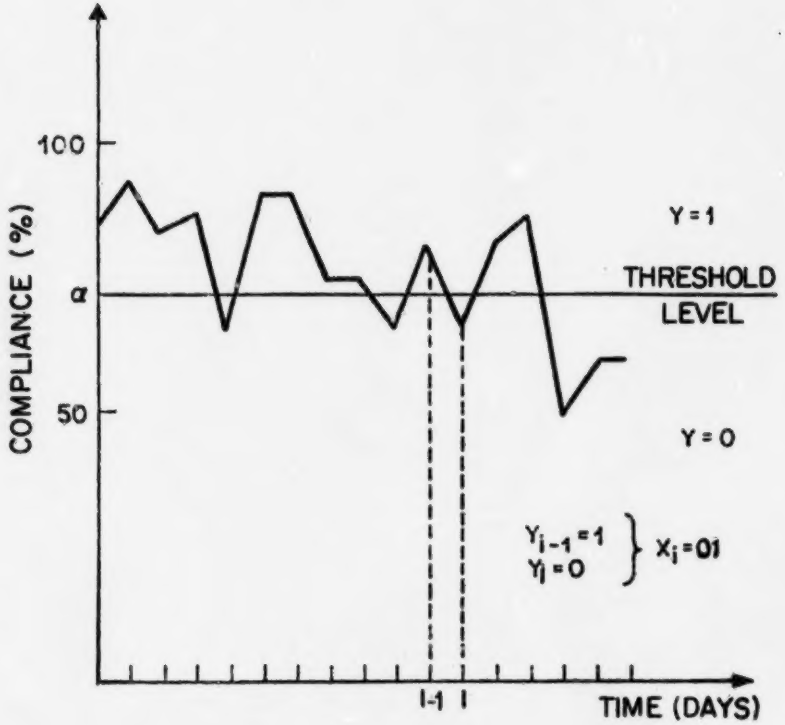

Fig. 15 Output quantization as a function of α.

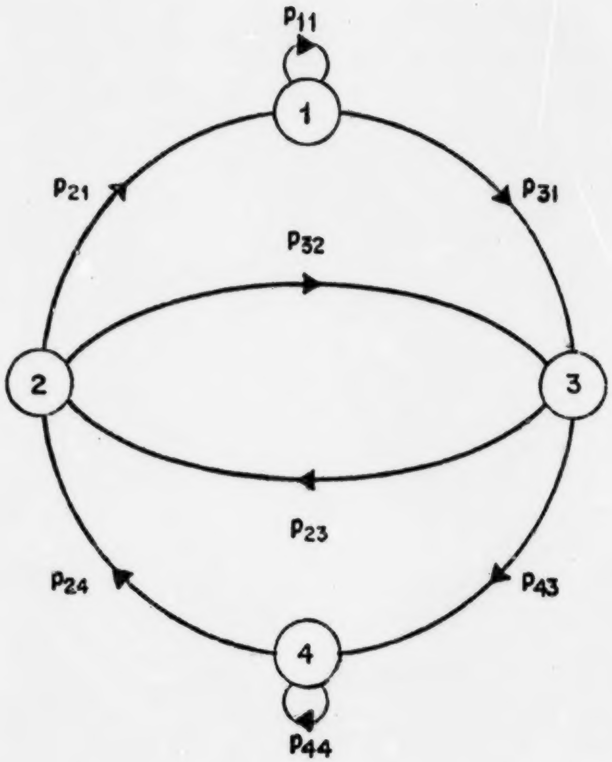
P11
1
P21
P31
P32
2
3
P23
P24
P43
4
P44

Fig. 16 Finite state machine model.

where $0 \leq \alpha \leq 100\%$. There are four possible states x_i defined as the concatenation of the output over two consecutive days*, i.e.,

$$x_i = y_i || y_{i-1} \tag{19}$$

Thus, the state of the machine on the i-th day is based on the compliance on that day and the compliance on the previous day. For example, assume $x_{i-1} = 10$, which implies that $y_{i-1} = 1$. On the next day the machine makes a transition to state x_i and yields an output y_i. If $y_i = 0$ then $x_i = 01$, and if $y_i = 1$ then $x_i = 11$. It is noted that x_i cannot be 00 or 10, i.e., not all transitions are possible. Specifically, only two transitions are possible from each state. It is convenient on occasion to drop the binary notation and adopt the following convention:

00 = state 1, 01 = state 2, 10 = state 3, and 11 = state 4.

The set of the transition probabilities with respect to a threshold level α can be represented by the state transition matrix $P(\alpha,u)$

$$P(\alpha,u) = \begin{bmatrix} p_{11}(u) & p_{12}(u) & 0 & 0 \\ 0 & 0 & p_{23}(u) & p_{24}(u) \\ p_{31}(u) & p_{32}(u) & 0 & 0 \\ 0 & 0 & p_{43}(u) & p_{44}(u) \end{bmatrix}_{\alpha} \tag{20}$$

where p_{kj} denotes the probability of transition from state j to state k. Zero entries indicate that the corresponding transitions are not allowable. For each α the state transition matrix can take one of two values: $P(\alpha,1)$ when enforcement takes place $(u = 1)$, and $P(\alpha,0)$ in the absence

---

[*] Higher order models can be generated by defining the state as the concatenation of the output over n consecutive days. However, the increasing complexity from using a model of order 2^n, and the inaccuracies introduced from trying to estimate 2^{n+2} transition probabilities from 118 data points make $n = 2$ the only practical choice.

of enforcement ($u = 0$). $P(\alpha,u)$ is a Markov matrix[13], i.e.,

$$\sum_{k=1}^{4} p_{kj} = 1; \quad j = 1,2,3,4 \tag{21}$$

with one eigenvalue equal to unity since the system is ergodic. The structure of the model is displayed graphically in Figure 16.

Numerical values for the elements of the state transition matrix $P(\alpha,u)$ are obtained by processing the experimental data using a simple algorithm. The transition probabilities for any given value of α are computed from

$$p_{kj}(v) = \frac{n_{kj}(v)}{n_j(v)}; \; v = 0,1; \quad k,j = 1,2,3,4$$

where $n_j(v)$ is the number of times the system makes a transition from state j with input $u = v$, and $n_{kj}(v)$ is the number of times the transition from state j is to state k with $u = v$.

Probability matrices have been calculated for $\alpha = 50,55,\ldots,95$. The restriction to values of $\alpha \geq 50$ is necessitated by the data available in Figure 14. There are very few points when the compliance is less than 50%. Elements of the probability transition matrices for such values of α would be meaningless.

THE SIMULATION MODEL

If the effect of a particular input sequence $\{u_i\}$ on the compliance level is to be investigated, then it is necessary to relate the Finite State Machine model and the transition probabilities to an estimate of compliance. This is accomplished by defining a simulation model with input u, output $\underline{z}$, and state $\underline{q}$. The output and the state are no longer a binary code, but denote probabilities.

$$\text{State:} \qquad \underline{q}(\alpha) = [q_1 q_2 q_3 q_4]^T \tag{22}$$

where q_k is the probability that the machine is in state k and

$$\text{Output:} \qquad \underline{z}(\alpha) = [z_1 z_2]^T \tag{23}$$

where z_1 is the probability that the compliance is less than or equal to α, and z_2 that it is larger than α. The input u is a scalar which takes the value 0 when no enforcement occurs and 1 when enforcement takes place.

Given the state transition matrices $P(\alpha,0)$ and $P(\alpha,1)$ and the state probability vector on the i-th day, $\underline{q}_i$, then the state on the i + 1st day can be calculated for any input u_i from

$$\underline{q}_{i+1}(\alpha) = [(1-u_i)P(\alpha,0) + u_i P(\alpha,1)]\underline{q}_i(\alpha) \tag{24}$$

$$\underline{z}_i(\alpha) = C\ \underline{q}_i(\alpha); \quad \underline{q}_0 = \underline{\xi} \tag{25}$$

where u_i is zero or one, and

$$C = \begin{bmatrix} 1 & 1 & 0 & 0 \\ 0 & 0 & 1 & 1 \end{bmatrix} .$$

For any $\alpha \geq 50\%$ and any particular input sequence $\{u_i\}$, the sequences of state and output probability vectors can be calculated. For example, if for a ten day interval

$$\{u_i\} = \{u_{10}\ u_9\ \cdots\ u_1\} = \{1101101001\} \text{ then}$$

$$\underline{q}_1 = P(1)\underline{q}_0$$

$$\underline{q}_2 = P(0)\underline{q}_1 = P(0)P(1)\underline{q}_0$$

$$\vdots$$

$$\underline{q}_{10} = P^2(1)P(0)P^2(1)P(0)P(1)P^2(0)P(1)\underline{q}_0$$

where the dependence on α has been suppressed for notational simplicity. The elements of the $\underline{z}$ vector take on a very special significance. For a given day i, the first element of the $\underline{z}$ vector predicts the probability that the compliance will be less than or equal to α for a given α, i.e.,

$$(z_1)_i = \Pr\{c_i \leq \alpha\} = F_{c_i}(\alpha)$$

This is, in fact, the probability distribution function of the random variable c_i.

For a given input sequence $\{u_i\}$, points on the distribution function can be calculated for $\alpha = 50,55,\ldots,95$ by utilizing the probability transition matrices for each value of α. Since this function is defined for $0 \leq \alpha \leq 100$, additional information is required to complete its description. First, it is assumed that $\Pr\{c_i \leq 100\} = 1$ and $\Pr\{c_i \leq 0\} = 0$. Next, the behavior of the probability distribution function for small values of $\alpha(\alpha < 50)$ is approximated. The input data in Figure 14 indicate that compliance is almost always greater than 50%. Therefore, it will be assumed that the probability for the compliance to be less than or equal to 50% is very small. The function in this region may be modeled by any monotonically increasing curve from $\alpha = 0$ to $\alpha = 50$. For simplicity the exponential was chosen; it was sampled at $\alpha = 5,10,\ldots,45$ resulting in a complete set of discrete data points. Finally the probability distribution function is assumed to be a piecewise continuous function of α. In particular, the function remains constant for values of $\alpha = \hat{\alpha} \pm 2.5$, where $\hat{\alpha} = 5,10,\ldots,90,95$.

The probability density function (PDF) of the random variable c_i can be found by differentiating the probability distribution function

$$P_{c_i}(\alpha) = \frac{d}{d\alpha} F_{c_i}(\alpha) \qquad (26)$$

However, since the distribution function is piecewise constant, the density function will be a sequence of impulses at values of α where the distribution function is discontinuous. The amplitude of each impulse is equal to the discontinuity in the distribution function at that value of α.

The points of discontinuity are contained in the set

$$\alpha_j \begin{cases} \alpha_0 = 0 \\ \\ \alpha_j = 5j-2.5; \quad j = 1,2,\ldots,20 \end{cases}$$

Then the PDF is defined as

$$p_{c_i}(\alpha) = \sum_{j=1}^{20} p_j \delta(\alpha-\alpha_j) \tag{27}$$

where

$$p_j = \Pr(\alpha \leq \alpha_j) - \Pr(\alpha \leq \alpha_{j-1}).$$

Given the density function for each day i, one can compute statistics relating to the compliance on that day. In particular, the expected value, $E(c_i)$, can be computed.

$$E(c_i) = \sum_{j=1}^{20} \alpha_j p_j \tag{28}$$

The model was simulated with the actual enforcement schedule from the data in Figure 14. Several measures of the deviation between actual and predicted levels of compliance were within acceptable bounds. For example, the mean square error was 2.5% while the mean absolute error was 12%.

ENFORCEMENT POLICIES

Now that the simulation model has been defined, enforcement policies can be simulated and their effect on compliance evaluated. Policies can be classified into deterministic and random ones. In each case, a specific policy is characterized by a pair of numbers (NT,T), where NT is the number of days enforcement takes place over a period of T days. For example, a (1,6) deterministic policy might mean that enforcement would take place each and every Monday (there is no enforcement on Sundays). However, a

(1,6) random policy means that the parking restrictions are enforced once every week, one week on Monday, the next week on Thursday, etc. Note that the frequency of enforcement, defined by f = NT/T,does not characterize uniquely an enforcement policy. A (1,6) and a (2,12) policy yield the same frequency. The former, however, guarantees that there will be one enforcement day during a period of 6 days, while the latter guarantees two enforcement days over a period of twelve days, e.g. on every tenth and twelfth day. This distinction led to the concept of enforcement gap. It is defined as the number of consecutive days on which enforcement does not take place. Maximum gap (MG) is the largest possible gap that could occur for a particular enforcement policy. For the (1,6) policy, the MG is 10. This would occur if enforcement took place on days 1 and 12. For the (2,12) policy, the MG is 20 occurring when two days of enforcement took place on days 1 and 2 and the next two enforcements on 23 and 24. In general, MG = 2(N-NT). So random policies with the same f but different (NT,T) can be quite dissimilar.

A wide variety of deterministic and random policies were simulated[14], including the limiting cases. As expected,the total enforcement policy (1,1) yielded a high expected value for the level of compliance (84%) within ten days. However, it is impractical to implement since it requires the daily deployment of a large number of officers. Rather than examine all possible pairs (NT,T), only implementable policies were analyzed in detail. Since field studies[12] have indicated that three days of enforcement within a twelve day period can sustain a high level of compliance to the no-parking regulations, the simulation results for deterministic and random policies with frequency 1/4 are presented here.

In the case of a deterministic policy , enforcement would occur every fourth day (Sundays excluded). A typical sequence would be: Monday, Friday, Wednesday, Monday, ... The simulation results are presented in Figure 17. The output exhibits a transient followed by a clearly periodic response. The response of the system to a periodic input is

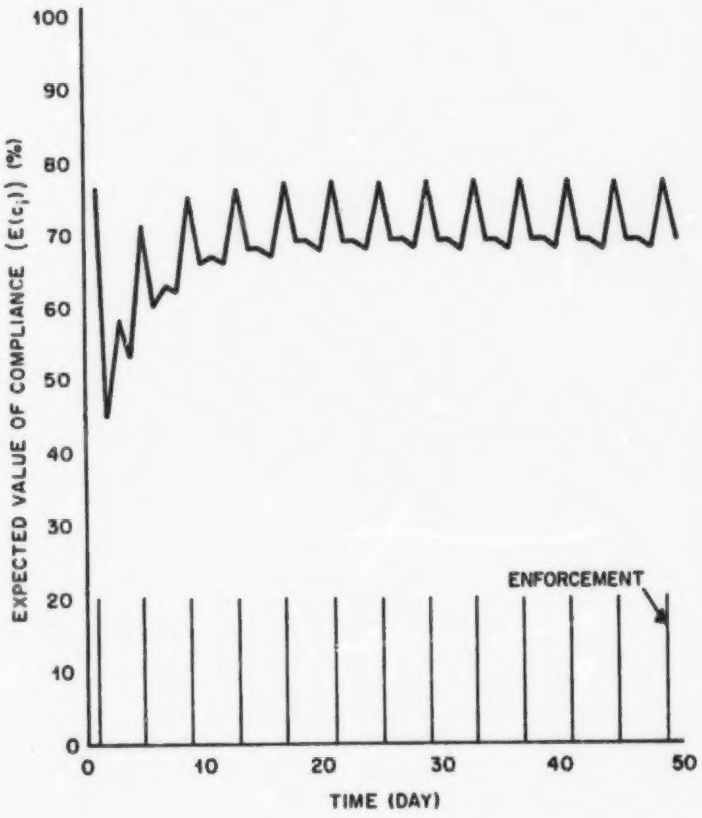

Fig. 17 Effect of deterministic policy (1, 4).

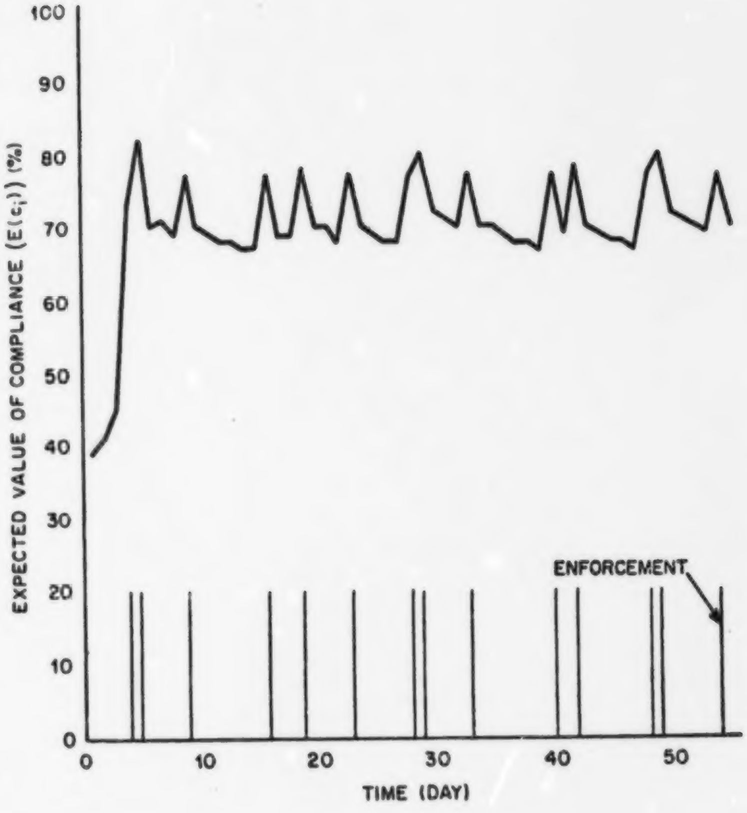

Fig. 18 Effect of random policy (1, 4).

periodic. The model predicts actual behavior: after two weeks, the system identification period, the potential violator realizes that enforcement occurs every fourth day and adapts his behavior accordingly so as to maximize parking convenience and minimize cost (tickets). Actual compliance increases on enforcement days and drops even more sharply than indicated in Figure 17 during the enforcement gap. To counteract this adaptive behavior random policies must be considered.

Three random policies with f = 1/4 were analyzed: (1,4), (2,8), and (3,12). In all cases, the maximum value of the expected compliance was approximately 81%. The longest enforcement gaps that occurred during the simulation were 6, 7, and 12 days, respectively, while the maximum possible ones are 6, 12, and 18. For this reason, the policy (1,4), Figure 18, is preferable. Lowering the frequency below 1/4 resulted in unsatisfactory compliance levels and longer enforcement gaps. Compliance was, in general, below 70% except on days enforcement took place.

Mixed policies were also studied, i.e., policies where there is one frequency during an initial period, and a second, lower frequency, from then on. It has been common practice to assign an additional team of enforcement officers to an area that has been without adequate enforcement for a long period of time and enforce rigorously the regulations on a daily basis for a period of 3-4 weeks. Then the additional officers are transferred to another area. Actual observed behavior indicated that although this policy yields an immediate increase in compliance the long term effect is negligible. The simulation results confirmed the observations and proved that this type of "saturation ticketing" efforts not followed up by steady-state policies are wasteful and not worth the high expenditure in additional manpower required for their implementation.

ENFORCEMENT SCHEDULE

Once a desired input sequence $\{\underline{u}\}$ is chosen, a routing schedule can be devised for officers issuing tickets. Enforcement schedules related to the expected value of compliance can be used to route officers into areas where the compliance level should be increased.

Although the model is simple, several parameters are required to specify it. These include the expected value of compliance $E\{c_i\}$, the time required to issue tickets (T_t), the walking speed of the officer (v), the total time allotted for the officer to canvass the area (T_M), information related to blockside length (L), and number of parking spaces on the blockside (N).

The number of illegally parked cars (I) on the j-th blockside can be defined as:

$$I_j = [1 - E\{c_i\}/100] \cdot N_j \tag{29}$$

where I_j is truncated to the largest integer which does not exceed the value of that expression. The time t_j to canvass the j-th block and issue summonses to all illegally parked cars is:

$$t_j = I_j T_t + L_j/v \tag{30}$$

The total time t necessary to cover the route is given by

$$t = \sum_{j=1}^{M} t_j \leq T_M \tag{31}$$

where M is the number of blocks covered.

Since the model was based on data that came from metered zones, T_M was set equal to one hour, the period between 8 and 9 A.M. during which no parking is permitted at metered spaces. When data become available for nonmetered areas and the appropriate state transition matrices are evaluated, then the procedure can be extended to route officers for an entire day.

Typical results are presented for the first twelve days of enforcement by an officer implementing a (3,6) random policy. It was assumed on the

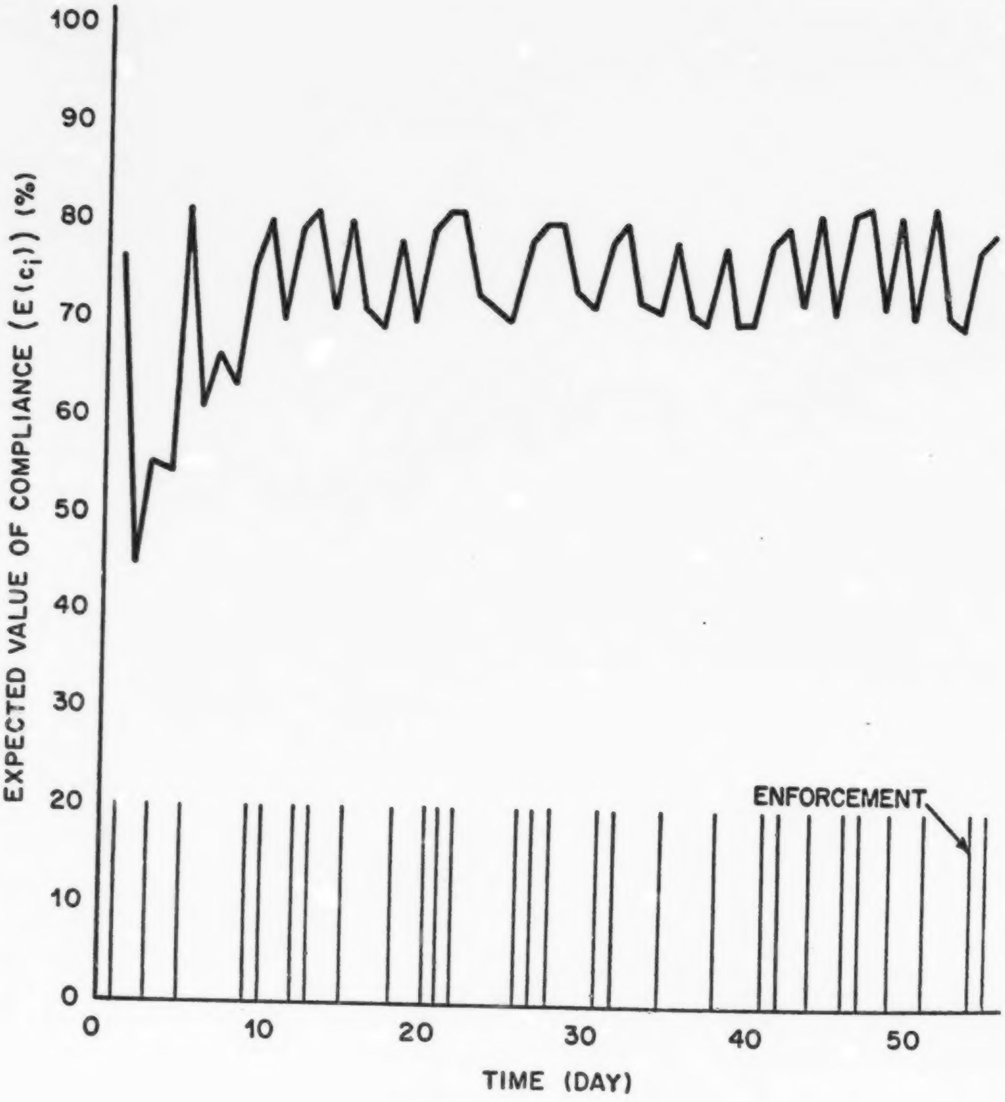

Fig. 19 Effect of random policy (3, 6).

basis of experimental evidence[15] that it takes 1.5 minutes to write a ticket and that an officer can walk at the rate of 3 miles/hr.

The (3,6) policy, Figure 19, specified enforcement on days 1, 3, 5, 9, 10 and 12. A computer algorithm was developed that included the simulation model; information about blockside lengths and number of parking spaces was obtained from the data bank. The results are summarized below:

Table 8. ROUTE STATISTICS

	Day 1	Day 3	Day 5	Day 9	Day 10	Day 12
Route Time (min.)	59	56	59	58	59	58
Tickets Issued	23	30	21	27	21	22
Blocks covered	33	15	37	23	37	34
Length covered (feet)	6455	2934	7232	4501	7232	6639

On day 1 the compliance level is 75.8%; the officer can cover 33 blocks and issue 23 tickets. Two days later, the officer "surprises" violators - the compliance level is only 55.4%. The officer can cover only 15 blocks but he issues 30 tickets. However, two days later on day 5, the people are expecting enforcement and compliance is up to 81.4%. The officer now covers as many as 37 blocks while issuing only 21 tickets. As the compliance level drops the officer covers fewer blocks and issues more tickets. For the enforcement days following the fifth day, the officer covers generally more than 30 blocks and issues 20-22 tickets. The routing for the first and second enforcement days is illustrated in Figure 20.

The statistics from the results are quite revealing when compared to actual practice. For example, the Traffic Department considers 20 to 30 summonses per Meter Maid per day to be adequate[15]. The figures listed in the outputs should be considered as maximum limits which might be achieved if the personnel were assigned exclusively to ticketing and were operating at top efficiency. It would probably be more realistic to cut the route

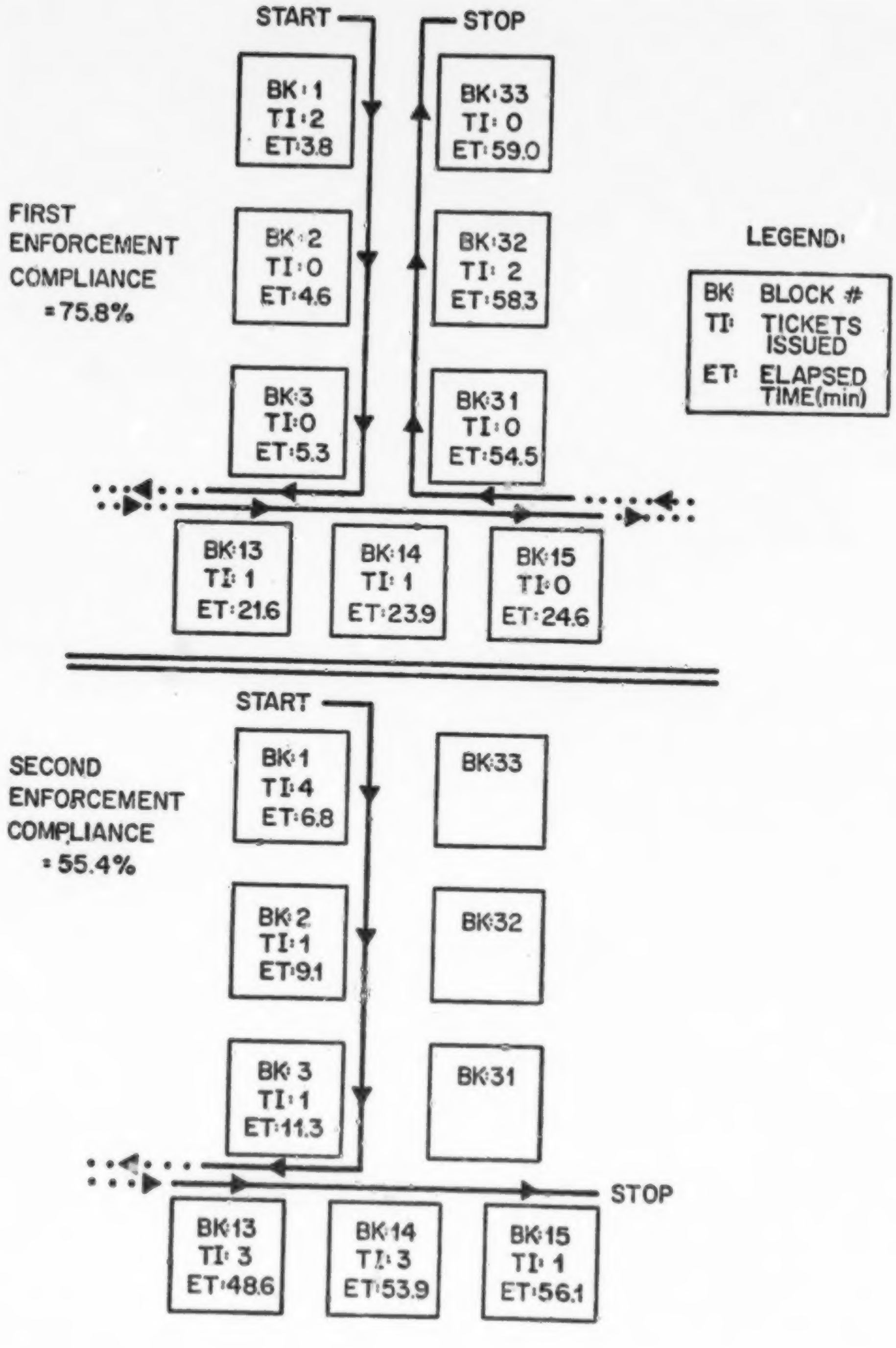
START
STOP
BK:1 TI:2 ET:3.8
BK:33 TI:0 ET:59.0
FIRST ENFORCEMENT COMPLIANCE =75.8%
BK:2 TI:0 ET:4.6
BK:32 TI:2 ET:58.3
LEGEND:
BK: BLOCK #
TI: TICKETS ISSUED
ET: ELAPSED TIME(min)
BK:3 TI:0 ET:5.3
BK:31 TI:0 ET:54.5
BK:13 TI:1 ET:21.6
BK:14 TI:1 ET:23.9
BK:15 TI:0 ET:24.6
START
SECOND ENFORCEMENT COMPLIANCE =55.4%
BK:1 TI:4 ET:6.8
BK:33
BK:2 TI:1 ET:9.1
BK:32
BK:3 TI:1 ET:11.3
BK:31
STOP
BK:13 TI:3 ET:48.6
BK:14 TI:3 ET:53.9
BK:15 TI:1 ET:56.1

Fig. 20 Enforcement schedules.

coverage distance in half - that may be a truer estimate of what may be accomplished. However, it is still far greater than what is presently achieved.

SECTION VIII

OPTIMAL ENFORCEMENT OF PARKING REGULATIONS

An analytical model that describes the dynamics of the interactions between enforcement and level of compliance was developed in Section VII. From actual data, a stochastic finite state machine relating enforcement to level of compliance was obtained. Simulations were then carried out using several periodic and random input policies to determine the effectiveness of those policies in raising and keeping compliance at a desired level. The desire to investigate the theoretical counterpart of those simulation results inevitably led to the formulation of Optimal Control problems which reflected the interaction between the cost of enforcement (manpower) and the level of compliance. The objective of this section is, therefore, to determine optimal, implementable enforcement strategies subject to operational and budgeting constraints so that a realistic measure of the cost be minimized. This cost functional embodies the real cost of enforcement, i.e., manpower which must be deployed to enforce the regulations, and the cost (or penalty) of entering some states in which the level of compliance to parking regulations is relatively low compared to a desired level.

OPTIMAL CONTROL PROBLEMS: FORMULATION

Several optimization problems can be formulated depending on the choice of a cost criterion and the type of output measurements. Since we are interested in the enforcement schedule for a fixed number of days, i.e., weekly schedules or monthly schedules, only the finite time horizon case will be discussed. Let us assume that we are looking for the N-day enforcement schedule. The state $x(k)$ of the system on the k-th day can take its value in the finite state space $S = \{1,2,3,4\}$. The sequence $x(k)$, $k=0,1,2,\dots, N$ can be regarded as a Markov chain with the transition probability $p_{ij}(u(k))$, where $p_{ij}(u=o)$ and $p_{ij}(u=1)$ have been defined as the (i,j) th elements of the two stochastic matrices P_o and P_1, respectively. Notice that the determination of P_o and P_1 depends upon the choice of the threshold level α. We will formulate the optimal control problem for a fixed value of α.

From the mathematical model derived in Section VII, we can relate $p_{ij}(u(k))$ to $p_{ij}(u=o)$ and $p_{ij}(u=1)$ as follows.

$$p_{ij}(u(k)) = (1-u(k))\; p_{ij}(u=o) + u(k)\; p_{ij}(u=1) \qquad (32)$$

Depending upon the information available, there are two different ways of processing the experimental data. In the first case it is assumed that an officer knows the level of compliance on that same day C_k, so that depending upon C_k (or equivalently the state x(k)) the enforcement schedule u(k) is decided. Such a situation can arise as follows. An officer is issuing summonses in the afternoon during the period from 12 to 2 P.M. The enforcement is based upon information on compliance gathered during the morning assignments by other officers or sanitation foremen, or mechanical sweeper operators. Given the compliance on the previous day, C_{k-1}, he can identify the current state of the system x(k). Then by means of the control law, he can determine the optimum amount of enforcement u(k) which is to be used between 12 and 2 P.M. If this is the manner in which data were collected, then the state transition matrices $P_o = \{p^o_{ij}\}$ and $P_1 = \{p^1_{ij}\}$ should be defined as,

$$\begin{aligned} p^o_{ij} &\triangleq \text{prob}\,\{x(k+1) = i \mid x(k) = j \; ; \; u(k) = o\} \\ p^1_{ij} &\triangleq \text{prob}\,\{x(k+1) = i \mid x(k) = j \; ; \; u(k) = 1\} \end{aligned} \qquad (33)$$

In the second case information regarding the level of compliance on that same day is not available, so that the enforcement schedule is decided according to the previous day's compliance. For example, assume the period of enforcement is between 8 and 9 A.M. Because the no-parking regulations are not in effect prior to 8 A.M., measurements are not possible. It would be appropriate to assume that the measurement of compliance (i.e. C_k) can be performed simultaneously with the issuing of summonses. At the end of the enforcement assignment the officer returns to his precinct with information regarding C_k. Now the state of the system (i.e. x(k)) can be determined from C_{k-1} and C_k. Therefore, the state x(k) can be identified only after the issuance of summonses, u(k). The amount of enforcement which will be used on the next morning (i.e. u(k+1)) should be determined from x(k) and not x(k+1). In this case, a model which includes delayed state observation is necessary. Consequently, the appropriate definitions of the state transition matrices $P_o = \{p_{ij}^o\}$ and $P_1 = \{p_{ij}^1\}$ should be

$$\begin{aligned} p_{ij}^o &\triangleq \text{prob}\,\{x(k) = i \mid x(k-1) = j\ ;\ u(k) = o\} \\ p_{ij}^1 &\triangleq \text{prob}\,\{x(k) = i \mid x(k-1) = j\ ;\ u(k) = 1\} \end{aligned} \tag{34}$$

Therefore, the main issue in selecting the model of the optimal control problem which matches with actual experimental data is the following: did the officer know the level of compliance C_k on k-th day before he decided the enforcement schedule or not? Analysis of the experimental data can lead to the answer in the following manner. Let us assume that by using either (33) or (34), two state transition matrices P_o and P_1 have been obtained from the actual data to yield the discrete-time equation

$$\underline{q}(k+1) = [\ (1-u)\ P_o + u\ P_1\ ]\ \underline{q}(k) \tag{35}$$

where $\underline{q}(k)$ is a 4-dimensional probability vector with the i-th element denoting the probability that at time k the system is in state i. Let us define

$$z(k) = \underline{y}^T\ q(k) \tag{36}$$

for all k, where $\underline{y}^T$ is a 4-dimensional row vector

$$\underline{y}^T = [\ 1,\ 1,\ 0,\ 0\ ] \tag{37}$$

Then z(k) can be expressed as

$$z(k) = \text{prob}\ \{x(k) = 1\} + \text{prob}\ \{x(k) = 2\}$$

or equivalently,

$$z(k) = \text{prob}\ \{C_k \leq \alpha\} \tag{38}$$

If the system is in state 1 or state 2, then the compliance C_k is less than or equal to threshold value α. Therefore, z(k) represents the probability of level of compliance being unsatisfactory with respect to α. It is a natural assumption that the probability of entering the states corresponding to low compliance when no enforcement takes place (i.e., u = o) should be no less than the probability when total enforcement (i.e. u = 1) takes place. Therefore, we have

$$z(k+1) \Big|_{u = o} \geq z(k+1) \Big|_{u = 1} \tag{39}$$

or from (34),

$$\underline{\gamma}^T P_o \underline{q}(k) \geq \underline{\gamma}^T P_1 \underline{q}(k) \tag{40}$$

Also, since P_o and P_1 have the form (20) and the system can be in any one of four possible states, the inequality (40) is equivalent to,

$$\begin{aligned} p_{11}^o &\geq p_{11}^1 \\ p_{12}^o &\geq p_{12}^1 \\ p_{23}^o &\geq p_{23}^1 \\ p_{24}^o &\geq p_{24}^1 \end{aligned} \tag{41}$$

The inequalities (41) comprise the conditions that the model relating compliance to enforcement should satisfy henceforth. The state transition matrices for all threshold values have been obtained from the experimental data by using two different definitions (33) and (34). Then the conditions (41) were used to select the model which describes the dynamical behavior of the data better. The numerical results reveal that the matrices obtained by using definitions (34) are superior to those obtained by using definitions (33) in satisfying these basic requirements.

This conclusion is in full agreement with the actual practices of the enforcement agencies. Recall that the measured compliance refers to a no-parking regulation between 8 and 9 A.M. Because of the early hour, measurements are not possible. Therefore, the officers' enforcement schedule must be based upon C_{k-1} and not C_k. Since the delayed state observation yields better description of the data and reflects the actual situation, the mathematical model with delayed state observation will be employed in the formulation of the optimal control problem.

Let us assume the cost (or loss) of being in state i be c_i for all $i = 1,2,3,4$. The cost c_i is scalar and non-negative. It would be appropriate for the cost of entering either state 1 or state 2 to be higher than that of entering either state 3 or state 4. This is because states 1 or 2 imply that the compliance is below or equal to the fixed threshold level α, while states 3 or 4 indicate that the compliance is greater than α. The cost of enforcement should also be introduced, since it reflects the manpower that must be deployed to enforce the regulations. Furthermore since the level of enforcement u is proportional to the manpower needed to implement it, the cost is taken to be ru^2 where r, the weighting coefficient, is assumed to be a positive constant. The instantaneous cost associated with the state x(k-1) and control u(k) is defined as the sum of the cost of being in state x(k-1) and the cost of using u(k) as an enforcement at time k and is denoted by L(u(k), x(k-1), k). If x(k-1) = i, then L(u(k), x(k-1), k) takes the following value.

$$L(u(k)\ ,\ x(k-1) = i,k) = ru^2(k) + c_i \qquad i = 1,2,3,4 \tag{42}$$

The terminal cost f(x(N)) is defined as

$$f(x(N)) = c_j\ ,\ \text{if } x(N) = j \text{ and } j = 1,2,3,4 \tag{43}$$

The total cost of the process is defined as

$$J = f(x(N)) + \sum_{k=1}^{N} L(u(k)\ ,\ x(k-1),\ k) \tag{44}$$

The optimization problem is the determination of an admissible control law, i.e., a relationship between the observed output and the control signal, such that the expected value of the total cost J is minimized. The control law can be considered as consisting of two parts: the estimation of the state of the system from the observed output and the calculation of the control from the estimated state. From the mathematical model in Section VII, we know that the actual observable output on the k-th day is the compliance on that day, i.e. C_k. Assuming noise-free measurement of the compliance, there exists a functional correspondence between the state of the system and the observed compliance for a fixed threshold value α.

$$\begin{aligned} x(k) &= 1 \quad \text{if} \quad C_k \le \alpha \quad \text{and} \quad C_{k-1} \le \alpha \\ x(k) &= 2 \quad \text{if} \quad C_k \le \alpha \quad \text{and} \quad C_{k-1} > \alpha \\ x(k) &= 3 \quad \text{if} \quad C_k > \alpha \quad \text{and} \quad C_{k-1} \le \alpha \\ x(k) &= 4 \quad \text{if} \quad C_k > \alpha \quad \text{and} \quad C_{k-1} > \alpha \end{aligned} \tag{45}$$

The mapping is displayed graphically in Fig. 21.

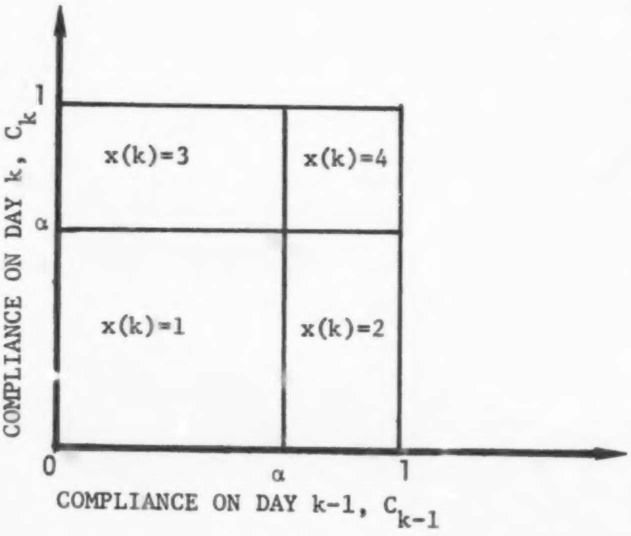

Fig. 21. Relationship between state and compliance for given α.

Because of this functional relationship between state and compliance, it can be assumed that the state of the system is available for feedback. We are interested in determining an admissible control signal as a function of the observed state such that the expected value of the total cost is minimized.

The formal statement of the optimal control problem is given as follows.

> Let the sequence $x(k)$, $k = 0,1,2,..,N$ be a Markov chain with the transition probability
>
> $$p_{ij}(u(k)) \triangleq \text{prob}\,\{x(k) = i \mid x(k-1) = j \,,\, u(k)\}$$
> $$= (1 - u(k))\, p^{o}_{ij} + u(k)\, p^{1}_{ij}\,.$$
>
> Let the total cost of the process be defined as
>
> $$J = f(x(N)) + \sum_{k=1}^{N} L(u(k),\, x(k-1),\, k)$$
>
> where L and f are defined as (42) and (43) respectively. Determine control law, $u \epsilon U$, that minimizes the expected value of the total cost J, $E[J]$, under the assumption that the state of the system can be measured without noise.

Depending on the set of admissible controls, two different problems can be formulated.

> (Case 1) The set of admissible controls U consists of two binary numbers, $U = \{o,1\}$.
>
> (Case 2) The control u assumes values in the closed interval $[o,1]$, i.e., $U = \{u \mid o \leq u \leq 1\}$

OPTIMAL CONTROL PROBLEMS: SOLUTION

The basic tool to solve the optimal control problems discussed will be Dynamic Programming because of its intuitive appeal for discrete-time systems. The method of Dynamic Programming is based upon the Principle of Optimality which can be expressed in the following way: Any control law which is optimal over the interval [i,N] is necessarily optimal over the interval [i+1,N]. The dynamic programming method of solving a multi-stage optimization problem makes use of the principle of optimality to convert the original problem into a family of simpler problems. Consider the last day of the optimization process, $k = N$. Let us assume that the system is in state i before the issuing of summonses $u(N)$, i.e., $x(N-1) = i$. Then the terminal cost of the system is given from the problem statement as

$$E \left[L(u(N), x(N-1), N) + f(x(N)) \mid x(N-1) = i \right] \tag{46}$$

Let us define $S^*(N,i)$ to be the minimum expected cost of (46). We then have

$$S^*(N,i) = \min_{u(N)} E \left[L\,(u(N), x(N-1), N) + f(x(N)) \mid x(N-1) = i \right] \tag{47}$$

or

$$\begin{aligned} S^*(N,i) = \min_{u(N)} \Big[& E \left\{ L(u(N), x(N-1), N) \mid x(N-1) = i \right\} \\ & + E \left\{ f(x(N)) \mid x(N-1) = i \right\} \Big] \end{aligned} \tag{38}$$

The first conditional expectation is deterministic since $x(N-1) = i$. Also, $x(N)$ can be a state j with probability $p_{ji}(u(N))$ and if $x(N) = j$, then $f(x(N)) = c_j$. We have from (38),

$$\begin{aligned} S^*(N,i) = \min_{u(N)} \Big[& L(u(N), x(N-1) = i, N) \\ & + \sum_{j=1}^{4} p_{ji}(u(N)) - c_j \Big] \end{aligned} \tag{49}$$

for all $i = i,2,3,4$

The equations (49) are the boundary conditions which initialize the recursive relation.

Let $$U_k^N \triangleq \{ u(k), u(k+1), \ldots, u(N) \} \tag{50}$$

and let $S^*(k,i)$ be the minimum expected cost from time k to the terminal time N, if the system is observed in state i at time k-1. That is,

$$S^*(k,i) \triangleq \min_{U_k^N} E\left\{f(x(N)) + \sum_{t=k}^{N} L(u(t), x(t-1), t) \mid x(k-1) = i\right\} \tag{51}$$

We rewrite Equation (51) as

$$\begin{aligned} S^*(k,i) \triangleq \min_{U_k^N} \Big[& E\left\{L(u(k), x(k-1), k) \mid x(k-1)=i\right\} \\ & + E\left\{f(x(N) + \sum_{t=k+1}^{N} L(u(t),x(k-1),t) \mid x(k-1) = i\right\} \Big] \end{aligned} \tag{52}$$

The first expectation in (52) is independent of u(t) for t greater than k. Also, its value is deterministic because x(k-1) is fixed as i. Hence, we have

$$\begin{aligned} S^*(k,i) = \min_{u(k)} \Big[& L(u(k), x(k-1) = i, k) \\ & + \min_{U_{k+1}^N} E\left\{f(x(N)) + \sum_{t=k+1}^{N} L(u(t), x(t-1), t) \mid x(k-1) = i\right\} \Big] \end{aligned} \tag{53}$$

We can use the nesting property of conditional expectations to rewrite the expectation in (53) as

$$E\left[E\left\{f(x(N)) + \sum_{t=k+1}^{N} L(u(t), x(t-1), t) \mid x(k)\right\} \mid x(k-1) = i \right] \tag{54}$$

Expression (54) can be rewritten as

$$\sum_{j} E\left\{f(x(N)) + \sum_{t=k+1}^{N} L(u(t),x(t-1),t) \mid x(k)=j\right\} \mathrm{prob}(x(k)=j \mid x(k-1)=i) \tag{55}$$

Since the quantity prob $(x(k)=j \mid x(k-1)=i)$ is non-negative, the expression (55) will be minimized if the inner conditional expectation is minimized for each possible j, j = 1,2,3,4. Let

$$\min_{U_{k+1}^N} E\left\{f(x(N)) + \sum_{t=k+1}^{N} L(u(t),x(t-1),t) \mid x(k)=j\right\} \triangleq S^*(k+1,j) \tag{56}$$

Then from (53),(55) and (56),

$$S^*(k,i) = \min_{u(k)} [L(u(k),x(k-1)=i,k) + \sum_{j=1}^{4} S^*(k+1,j)\ \mathrm{prob}(x(k)=j \mid x(k-1)=i)] \tag{57}$$

Equation (57) is the recursive optimization equation for $S^*(k,i)$. Since

$$\mathrm{prob}\ (x(k) = j \mid x(k-1) = i) \triangleq p_{ji}(u(k))$$

We finally have

$$S^*(k,i) = \min_{u(k)} [L(u(k),x(k-1)=i,k) + \sum_{j-1}^{4} p_{ji}(u(k))\ S^*(k+1,j)] \tag{58}$$

for all $k = N-1,N-2,\ldots,0$. Furthermore, from

$$L(u(k),\ x(k-1) = i,k) = ru^2(k) + c_i$$

and the transition probability $p_{ij}(u(k))$ given as

$$p_{ij}(u(k)) = (1-u(k))\ p^o_{ij} + u(k)\ p^1_{ij}$$

equation (58) takes the form

$$S^*(k,i) = \min_{u(k)} \{ru^2(k) + c_i + \sum_{j=1}^{4} [(1-u(k))p^o_{ji} + u(k)p^1_{ji}]\quad S^*(k+1,j)\} \tag{59}$$

for all $k = N-1,N-2,\ldots,0$

for all $i = 1,2,3,4$.

Solution: Case 1

Since the control u can take the value of either 0 or 1, we have

$$S^*(k,i) = \min \{c_i + \sum_{j=1}^{4} p^o_{ji}\ S^*(k+1,j),\ r + c_i + \sum_{j=1}^{4} p^1_{ji}\ S^*(k+1,j)\} \tag{60}$$

The optimal control at time k, if the system has been observed in state i at time k-1, can be given as

$$u^*(k,i) = \begin{cases} 0 & \text{if } d(k,i) \geq o \\ 1 & \text{if } d(k,i) < o \end{cases} \tag{61}$$

where

$$d(k,i) = r + \sum_{j=1}^{4} (p_{ji}^{1} - p_{ji}^{o})\, S^{*}(k+1,j) \tag{62}$$

for all k = N-1,N-2,...,0. As a boundary condition at time N, we have

$$S^{*}(N,i) = \min \{c_i + \sum_{j=1}^{4} p_{ji}^{o}\, c_j \, , \; r + c_i + \sum_{j=1}^{4} p_{ji}^{1}\, c_j \} \tag{63}$$

Solution: Case 2

Equation (59) can be rewritten as

$$S^{*}(N,i) = \min_{u(k)} \{ru^{2}(k)+u(k) \sum_{j=1}^{4} b_{ji}\, S^{*}(k+1,j) + c_i + \sum_{j=1}^{4} a_{ji}\, S^{*}(k+1,j)\} \tag{64}$$

where

$$a_{ji} = p_{ji}^{o}$$

$$b_{ji} = p_{ji}^{1} - p_{ji}^{o} \tag{65}$$

Minimization yields the control at time k if the system is in state i at time k-1

$$u(k,i) = -\frac{1}{2r} \sum_{j=1}^{4} b_{ji}\, S^{*}(k+1,j), \quad j = 1,2,3,4 \tag{66}$$

However, since the admissible control is constrained to be in the closed interval $[o,1]$, the optimal control law u^{*} is

$$u^{*}(k,i) = \begin{cases} o & , \text{ if } u(k,i) \leq o \\ u(k,i) & , \text{ if } o < u(k,i) < 1 \\ 1 & , \text{ if } u(k,i) \geq 1 \end{cases} \tag{67}$$

Therefore, the sequences $S^{*}(k,i)$, all i, are the solution to a set of coupled non-linear difference equations of the form

$$\begin{aligned} S^{*}(k,i) &= c_i + \sum_{j=1}^{4} a_{ji}\, S^{*}(k+1,j) \quad ; \text{ if } u^{*}(k,i) = o \\ S^{*}(k,i) &= c_i + \sum_{j=1}^{4} a_{ji}\, S^{*}(k+1,j) - \frac{1}{4r} [\sum_{j=1}^{4} b_{ji}\, S^{*}(k+1,j)]^{2} \\ S^{*}(k,i) &= r + c_i + \sum_{j=1}^{n} (a_{ji}+b_{ji})\, S^{*}(k+1,j) \quad ; \text{ if } u^{*}(k,i) = 1 \end{aligned} \tag{68}$$

for all k=N,N-1,...,0 where the boundary condition is given as,

$$S^*(N+1,j) = c_j \tag{69}$$

NUMERICAL RESULTS AND SIMULATIONS

Since we are interested in the enforcement schedule for a fixed number of days, (i.e., weekly or monthly schedule) the optimization interval is finite. In particular it was assumed that schedules are prepared for intervals of two weeks, i.e., N=12, reflecting the fact that no enforcement takes place on Sunday. Since states 3 and 4 correspond to levels of compliance higher than the threshold α, there is no need to penalize the system for being in these states. Therefore, we set $c_3 = c_4 = o$ in the performance index; the remaining weighting coefficients to be chosen are r, c_1, and c_2.

The following observation can be made. As the weighting coefficient r increases with respect to c_1 and c_2 so that the cost of using manpower becomes prohibitively expensive, then the optimal control tends to become zero, i.e. $u(k) = o$ for all k. On the other hand, if the cost of entering the low compliance states 1 or 2 becomes high relative to the cost of manpower thus reflecting the high cost of inefficient delivery of various municipal services such as sanitation, health, and fire protection, then the optimal control policy tends toward total enforcement, i.e., $u(k)=1$ for all k. Based upon the optimal control laws derived earlier, numerical results have been obtained for various sets of values, c_1, c_2, and r. The solutions have been obtained in the form of two rectangular arrays, the Optimal Cost Array and the Optimal Control Array. The (k,j)th element of the array corresponds to the system being in state j on the k-th day of the optimization process. The size of each array is 12x4. The Optimal Cost Array is a table of the minimum expected cost $S^*(k,i)$, while the Optimal Control Array contains the optimal control schedule for all $k = 1,2,\ldots,12$ and for all $i = 1,2,3,4$. The numerical result for Case 1 in which $U = \{0,1\}$ is shown in Table 9 with parameter values fixed as

Table 9. OPTIMAL ARRAYS: $U = \{0,1\}$, $\alpha = 0.70$, $c_1 = c_2 = 3$, $r = 2$

(a) OPTIMAL COST ARRAY

Day	State 1	State 2	State 3	State 4
1	22.35	20.40	13.07	12.28
2	21.10	19.16	11.86	11.07
3	19.84	17.92	10.65	9.86
4	18.56	16.67	9.46	8.65
5	17.25	15.40	8.29	7.46
6	15.91	14.12	7.14	6.29
7	14.51	12.81	6.03	5.14
8	13.04	11.46	4.96	4.03
9	11.45	10.06	3.97	2.96
10	9.70	8.59	3.10	1.97
11	7.69	6.86	2.45	1.10
12	5.43	4.80	1.50	0.45

(b) OPTIMAL CONTROL ARRAY

Day	State 1	State 2	State 3	State 4
1	0.0	0.0	1.0	0.0
2	0.0	0.0	1.0	0.0
3	0.0	0.0	1.0	0.0
4	0.0	0.0	1.0	0.0
5	0.0	0.0	1.0	0.0
6	0.0	0.0	1.0	0.0
7	0.0	0.0	1.0	0.0
8	0.0	0.0	1.0	0.0
9	0.0	0.0	1.0	0.0
10	0.0	0.0	1.0	0.0
11	0.0	0.0	1.0	0.0
12	0.0	0.0	0.0	0.0

Table 10. OPTIMAL ARRAYS: $U = [\ 0,1\ ]$, $\alpha = 0.70$, $c_1 = c_2 = 3$, $r = 2$

(a) OPTIMAL COST ARRAY

Day	State 1	State 2	State 3	State 4
1	19.79	18.05	11.33	10.32
2	18.78	17.05	10.34	9.33
3	17.76	16.04	9.36	8.34
4	16.73	15.03	8.38	7.36
5	15.68	14.00	7.40	6.38
6	14.59	12.95	6.44	5.41
7	13.44	11.86	5.50	4.45
8	12.21	10.73	4.58	3.52
9	10.84	9.50	3.69	2.62
10	9.29	8.15	2.84	1.77
11	7.50	6.63	2.00	1.02
12	5.38	4.75	1.22	0.42

(b) OPTIMAL CONTROL ARRAY

Day	State 1	State 2	State 3	State 4
1	0.45	0.42	0.96	0.29
2	0.44	0.42	0.96	0.29
3	0.44	0.42	0.96	0.29
4	0.44	0.41	0.95	0.29
5	0.43	0.41	0.94	0.28
6	0.42	0.40	0.93	0.28
7	0.40	0.38	0.90	0.27
8	0.38	0.36	0.86	0.26
9	0.34	0.42	0.80	0.25
10	0.29	0.27	0.70	0.21
11	0.22	0.21	0.54	0.16
12	0.16	0.15	0.38	0.11

$c_1 = 3$, $c_2 = 3$ and $r = 2$. The threshold value α was chosen as 0.70. In Table 10, the result for Case 2 is shown with the same parameter values. It can be observed that the expected cost for Case 1 is generally higher than that of Case 2. This is because the latter allows more flexibility in the choice of control signal than the former when minimizing the cost functional.

These results are used to decide the actual enforcement schedule as follows. On the k-th day, an officer is issuing summonses (i.e. $u(k)$) between 8 and 9 A.M. The measurement of compliance (i.e. C_K) can be performed while enforcement takes place. After finishing enforcement, he returns to his precinct or district office and decides the state of the system (i.e. $x(k)$) from C_{k-1} and C_k by using the functional relations shown in Figure 21. Then he selects from the Optimal Control Array the level of enforcement that should be applied on the next morning (i.e. $u(k+1)$); it is the $(k+1,j)$th element of the Optimal Control Array if the state $x(k)$ was identified as j. Since the Optimal Control Array can be computed off-line prior to the two-week enforcement period, the determination of the enforcement schedule from the array can be made very conveniently at the district level where computational capability may not be readily available.

Some samples of the simulation results are shown in Table 11. The first table corresponds to Case 1 while the second one is for Case 2 of the optimal control problem with threshold value 0.70. In Figures 22 and 23, the optimal enforcement schedules are shown for the threshold value $\alpha = 0.70$ for $U = \{0,1\}$ and $U = [0,1]$, respectively. Using the generated input sequences it is possible to compute the expected level of compliance denoted by $E[C_k]$ and to compare the results between the two cases. By using Equation (28) of Section VII $E[C_k]$ was computed and the results are plotted graphically in Fig. 24. The solid line is for $U = \{0,1\}$ while the dotted line is for $U = [0,1]$. The average level of expected compliance for $U = \{0,1\}$ is about 0.75, while for $U = [0,1]$ about 0.79. Therefore, there occurs a small increase in the average

Table 11. SIMULATION RESULTS FOR $\alpha = 0.70$

(a) $U = \{ 0,1 \}$

Day k	State x(k)	Cost $S^*(k,i)$	Control $u^*(k,i)$
1	3	13.07	1.0
2	2	19.17	0.0
3	1	19.84	0.0
4	1	18.56	0.0
5	3	8.29	1.0
6	4	6.29	0.0
7	2	12.81	0.0
8	3	4.96	1.0
9	4	2.96	0.0
10	4	1.97	0.0
11	2	6.86	0.0
12	1	5.43	0.0

(b) $U = [0,1]$

Day k	State x(k)	Cost $S^*(k,i)$	Control $u^*(k,i)$
1	3	11.33	0.96
2	2	17.05	0.42
3	1	17.76	0.44
4	1	16.73	0.44
5	3	7.40	0.94
6	4	5.41	0.28
7	2	11.86	0.38
8	3	4.58	0.86
9	4	2.62	0.24
10	4	1.77	0.21
11	2	6.63	0.21
12	1	5.38	0.16

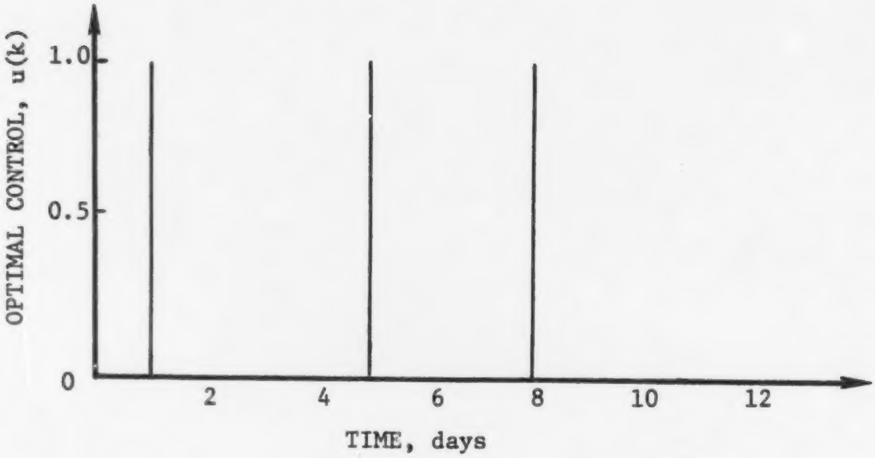

Figure 22. Optimal control schedule for U={0,1}

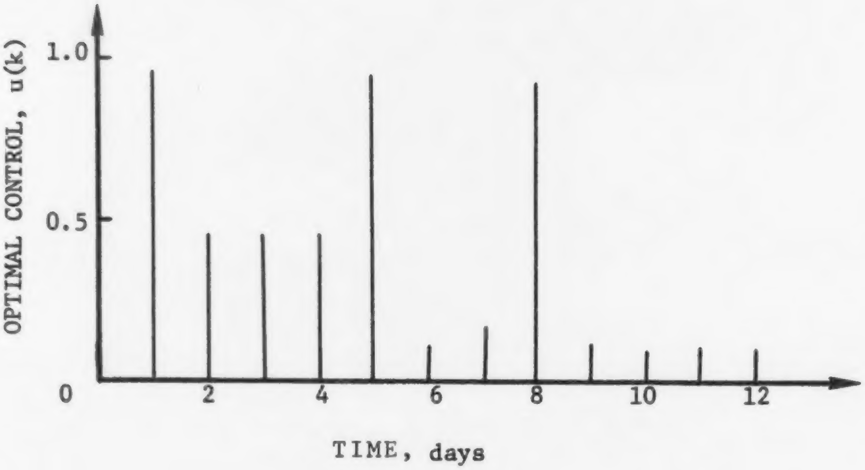

Figure 23. Optimal control schedule for U=[0,1]

expected compliance by allowing fractional values of enforcement. However, the total amount of enforcement for $U = \{0,1\}$ is just 3 units of manpower while for $U = [0,1]$ a total of 5.6 units of manpower have been used. It can be concluded that the reward for using nearly double the amount of expensive manpower is relatively small (an increase in compliance level of 0.04), so that the admissible control $U = \{0,1\}$ yields more desirable cost-effectiveness than $U = [0,1]$.

THE EFFECT OF THE WEIGHTING PARAMETERS

The three weighting coefficients r, c_1, and c_2 determine the numerical values of the solution to the optimization problem. In this section, the effect of these parameters on the minimum expected cost for $U = \{0,1\}$ is analyzed.

Let us denote by $E[J_i]$ the minimum expected total cost for the finite horizon (N=12) optimization process in which on the very first day the system has been observed to be in state i. Then the quantities $E[J_i]$, $i = 1,2,3,4$ correspond to the elements in the first row of the Optimal Cost Array. That is,

$$E[J_i] \triangleq S^*(1,i) \ , \ i = 1,2,3,4 \tag{70}$$

Recall that the quantity $E[J_i]$ or $S^*(1,i)$ has been computed recursively from terminal time (N=12) by using the recursive optimization equation,

$$S^*(k,i) = \min \{c_i + \sum_{1=j}^{4} p^{o}_{ji} \ S^*(k+1,j),\ r + c_i + \sum_{j=1}^{4} p^{1}_{ji} \ S^*(k+1,j)\} \tag{60}$$

with boundary condition,

$$S^*(N+1,i) \triangleq c_i$$

Now, let us define the normalized expected cost $T(k,i)$ as

$$T(k,i) = \frac{S^*(k,i)}{r} \tag{71}$$

Then by dividing both sides of Eq. (60) by r, and using the definition

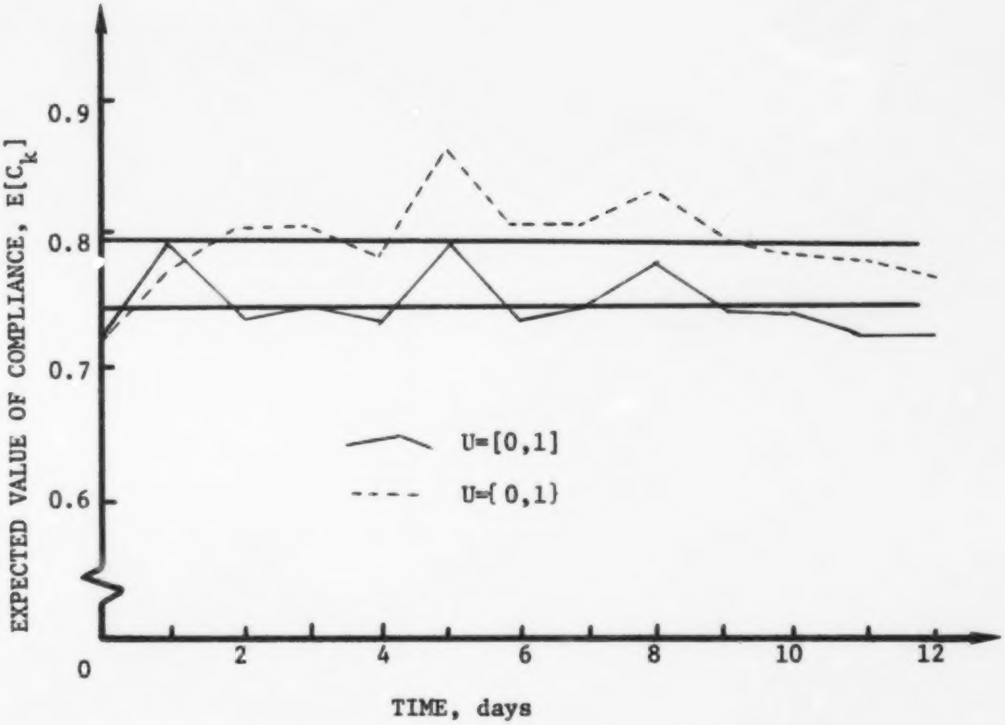

Figure 24. Expected compliance versus time.

(71), we have

$$T(k,i) = \min \{\frac{c_i}{r} + \sum_{j=1}^{4} p_{ji}^{o} \;\; T(k+1,j) \;\; , 1 + \frac{c_i}{r} + \sum_{j=1}^{4} p_{ji}^{1} \;\; T(k+1,j)\} \tag{72}$$

$$T(N+1,i) = \frac{c_i}{r}$$

which has the same functional form as Eq. (60) but with normalized coefficients. Therefore, it can be concluded that the normalized parameters are sufficient to characterize the relative values of $S^*(k,i)$. If we define $\bar{c}_1$ and $\bar{c}_2$ as

$$\bar{c}_1 = c_1/r \quad ; \quad \bar{c}_2 = c_2/r \tag{73}$$

then the analysis can be carried out in terms of the two normalized parameters $\bar{c}_1$, and $\bar{c}_2$ instead of the three original ones r, c_1 and c_2 . Now let us define the ratio of $\bar{c}_1$ and $\bar{c}_2$ as λ , i.e.,

$$\lambda = c_1/c_2 = \bar{c}_1/\bar{c}_2 \tag{74}$$

Thus, dividing both sides of Eq. (72) by $\bar{c}_2$ and using the definition

$$H(k,i) = T(k,i)/\bar{c}_2 \tag{75}$$

we obtain

$$H(k,i) = \min \{\frac{\bar{c}_i}{\bar{c}_2} + \sum_{j=1}^{n} p_{ji}^{o} \cdot H(k+1,j), \; \frac{1}{\bar{c}_2} + \frac{\bar{c}_i}{\bar{c}_2} + \sum_{j=1}^{4} p_{ji}^{1} \;\; H(k+1,j)\} \tag{76}$$

or, equivalently, by using (74) we have

$$\begin{aligned}
H(k,1) &= \min \left\{ \lambda + \sum_{j=1}^{4} p_{j1}^{o} \;\; H(k+1,j), \frac{\lambda}{c_1} + \lambda + \sum_{j=1}^{4} p_{j1}^{1} \cdot H(k+1,j) \right\} \\
H(k,2) &= \min \left\{ 1 + \sum_{j=1}^{4} p_{j2}^{o} \cdot H(k+1,j), \frac{\lambda}{c_1} + 1 + \sum_{j=1}^{4} p_{j2}^{1} \cdot H(k+1,j) \right\} \\
H(k,3) &= \min \left\{ \sum_{j-1}^{4} p_{j3}^{o} \;\; H(k+1,j), \; \frac{\lambda}{c_1} + \sum_{j=1}^{4} p_{j3}^{1} \cdot H(k+1,j) \right\}
\end{aligned} \tag{77}$$

$$H(k,4) = \min \left\{ \sum_{j=1}^{4} p^{o}_{j4} \cdot H(k+1,j) \; , \; \frac{\lambda}{\bar{c}_1} + \sum_{j=1}^{4} p^{1}_{j4} \cdot H(k+1,j) \right\} \tag{77}$$

with boundary conditions

$$\begin{aligned} H\,(N+1,1) &= \lambda \\ H\,(N+1,2) &= 1 \\ H\,(N+1,3) &= 0 \\ H\,(N+1,4) &= 0 \end{aligned} \tag{78}$$

Lemma 1 The quantity $H(k,i)$ for all $k = 1,2, \ldots ,N$ and $i = 1,2,3,4$, can be represented as,

$$H(k,i) = \min \left\{ w_{ki}(\lambda) + \frac{\beta_{ki}(\lambda)}{\bar{c}_1} \; , \; \gamma_{ki}(\lambda) + \frac{\delta_{k1}(\lambda)}{\bar{c}_1} \right\} \tag{79}$$

where w_{ki}, β_{ki}, γ_{ki}, δ_{ki} are functions only of λ and not of $\bar{c}_1$.

Proof (By induction)

At $k = N$, $H(N,i)$ satisfies the form of (79) by simple observation of Equations (77) and (78). Now let us assume $H(k,i)$ satisfies Eq. (79) for some k; at $k-1$ we have

$$H(k-1,i) = \min \left\{ f(\lambda) + \sum_{j=1}^{4} p^{o}_{ji} \cdot H(k,j), \; \frac{g(\lambda)}{\bar{c}_1} + h(\lambda) + \sum_{j=1}^{4} p^{1}_{ji} \cdot H(k,j) \right\}$$

$$= \min \left[f(\lambda) + \sum_{j=1}^{4} p^{o}_{ji} \cdot \min \left\{ w_{ki}(\lambda) + \frac{\beta_{ki}(\lambda)}{\bar{c}_1} \; , \; \gamma_{ki}(\lambda) + \frac{\delta_{ki}(\lambda)}{\bar{c}_1} \right\} , \right.$$

$$\left. \frac{g(\lambda)}{\bar{c}_1} + h(\lambda) + \sum_{j=1}^{4} p^{1}_{ji} \cdot \min \left\{ w_{ki}(\lambda) + \frac{\beta_{ki}(\lambda)}{\bar{c}_1} \; , \; \gamma_{ki}(\lambda) + \frac{\delta_{ki}(\lambda)}{\bar{c}_1} \right\} \right]$$

$$= \min \left\{ w_{k-1,i}(\lambda) + \frac{\beta_{k-1,i}(\lambda)}{\bar{c}_1} \; , \; \gamma_{k-1,i}(\lambda) + \frac{\delta_{k-1,i}(\lambda)}{\bar{c}_1} \right\}$$

Therefore, $H(k-1,i)$ also satisfies the form of (79). Since the statement is true for f=N, it follows by induction that it is true for all k, and Lemma 1 is proved.

__Theorem 1__ The minimum expected cost $S^*(k,i)$ can be represented as

$$S^*(k,i) = \frac{r}{\lambda} \cdot \min \{w_{ki}(\lambda).\bar{c}_1 + \beta_{ki}(\lambda) \ , \ \gamma_{ki}(\lambda).\bar{c}_1 + \delta_{ki}(\lambda)\} \qquad (80)$$

for all k = 1,2,..,N and i = 1,2,3,4.

__Proof__ The proof of the theorem follows from the previous lemma. Recall that from (71) and (75), we have

$$S^*(k,i) = r \ . \ T(k,i) = r \ . \ \bar{c}_2 \ . \ H(k,i)$$

Now from (74), we have

$$S^*(k,i) = r \ . \ \frac{\bar{c}_1}{\lambda} \ . \ H(k,i)$$

which is equivalent to

$$S^*(k,i) = r \ . \ \frac{\bar{c}_1}{\lambda} \ . \ \min \{w_{ki}(\lambda\} + \frac{\beta_{ki}(\lambda)}{\bar{c}_1} \ , \ \gamma_{ki}(\lambda) + \frac{\delta_{ki}(\lambda)}{\bar{c}_1} \ \}$$

Insertion of $\bar{c}_1$ inside the parenthesis leads to equation (80). This completes the proof of the theorem.

From the theorem, we can draw the following conclusions. If the values of r and λ are fixed, then depending upon the relative values of w_{1i}, β_{1i}, γ_{1i}, δ_{1i} the curve $E[\ J_i\ ]$ versus $\bar{c}_1$ is either a straight line or a concatenation of two straight lines as shown in Figure 25.

The curve actually represents the control law for the various values of c_1 and c_2 for the fixed value of r and λ.

Now let us investigate the relationship between the expected total cost $E[\ J_i\ ]$ and cost ratio λ for the fixed value of r and $\bar{c}_1$. We have the following lemma.

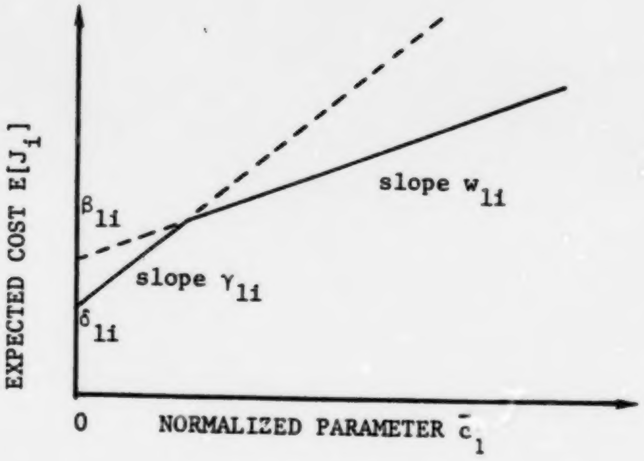

Figure 25. Expected cost vs. $\bar{c}_1$ for $\beta_{1i} \geq \delta_{1i}$ and $w_{1i} \leq \gamma_{1i}$

Lemma 2 The quantity H(k,i) for all k=1,2,..,N and i = 1,2,3,4 can be represented as,

$$H(k,i) = \min\{ a_{ki} + b_{ki}\lambda \; , \; c_{ki} + d_{ki}\, \lambda \} \tag{81}$$

where a_{ki}, b_{ki}, c_{ki} are some functions of $\bar{c}_1$ and independent of λ .

The proof of the Lemma 2 can be derived from equations (77) and (78) in a manner similar to that of Lemma 1. The following theorem is the direct result of Lemma 2.

Theorem 2 The minimum expected cost $S^*(k,i)$ can be represented as

$$S^*(k,i) = r\, \bar{c}_1 \cdot \min\{\frac{a_{ki}}{\lambda} + b_{ki} \; , \; \frac{c_{ki}}{\lambda} + d_{ki}\} \tag{82}$$

for all k = 1,2,.. ,N and i = 1,2,3,4 .

Since the coefficients a_{ki}, b_{ki}, c_{ki} and d_{ki} are derived from $\bar{c}_1$ and the elements of stochastic matrices P_o and P_1 are all non-negative, we can conclude that as the value of λ increases, the expected cost $S^*(k,i)$ decreases at the rate of $1/\lambda$. The curve E [J_i] versus λ for fixed values of r and $\bar{c}_1$, is either a hyperbola or a concatenation of two hyperbolas depending upon a_{1i}, b_{1i}, c_{1i} and d_{1i}. This is shown in Figure 26.

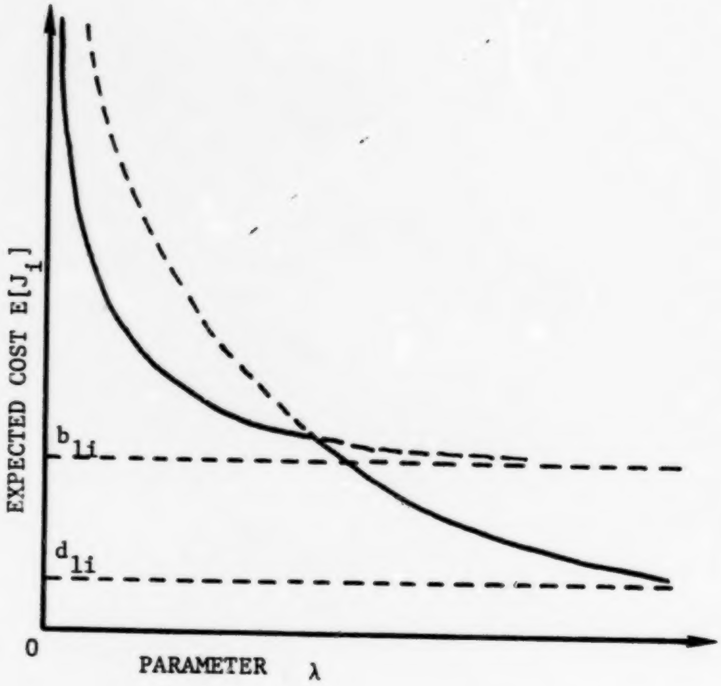

Figure 26. Expected cost vs. λ for $b_{1i} \geq d_{1i}$ and $a_{1i} \leq c_{1i}$

We have the following conclusions.

(i) The minimum expected cost for the optimal enforcement of parking regulations for a finite optimization interval increases as the relative cost, defined as the ratio of the cost of entering state 1 divided by the cost of manpower, increases. Therefore, as cost of entering the low compliance states, that is state 1 or state 2 increases, the total expected cost increases.

(ii) The minimum expected cost for the optimal enforcement of parking regulations decreases as the cost ratio (the cost of entering state 1 divided by that of entering state 2) increases. It is equivalent to say that as cost of entering state 2 decreases the total cost decreases as the ratio $1/\lambda$.

CONCLUDING REMARKS

It has been shown that the dynamics of the interaction between enforcement and level of compliance can be expressed in the form of a homogeneous time-invariant bilinear equation which yields a bilinear Markov chain[17] for the sequence of states of the system. The optimal control problem is the determination of implementable enforcement strategies, subject to operational and budgetary constraints, that minimizes a measure of the cost. The cost functional was defined in such a way as to embody the real cost of enforcement (manpower) which has to be deployed to enforce the regulations and the cost (or penalty) of entering low compliance states. The latter reflects the high cost of inefficient delivery of various municipal services.

The determination of simple solutions that can be computed off-line was a major factor in the choice of optimization methods because, at the district level, on-line computational capability may not be readily available. In addition to the one presented in this section, several other optimization problems were considered[18]. The method of information gathering, decision-making and the explicit and implicit objectives of enforcement are the distinguishing characteristics of the other formulations. The numerical results led to the following conclusions.

(i) The cost-effectiveness of using fractional amount of enforcement is slim, therefore non-economical.

(ii) If the cost of entering low compliance states is greater than 5 (i.e. $c_1 > 5$, $c_2 > 5$ while $c_3 = c_4 = 0$, $r = 1$), then the optimal control policy is total enforcement.

(iii) The minimum expected cost increases linearly; (possibly with two different slopes) as the relative costs ($\bar{c}_1$, $\bar{c}_2$) increase.

(iv) The minimum expected cost decreases as the cost ratio (λ) increases, or equivalently the cost of entering state 2 decreases as $1/\lambda$.

The enforcement schedules obtained from simulations using optimal controls are very similar to those obtained experimentally using the simulation methods described in Section VII. The major advantage of using optimal feedback control is the ability to determine daily the level of enforcement on the basis of the latest information regarding the level of compliance. Thus, if the compliance is high, the appropriate entry in the optimal control array may indicate that no enforcement is necessary, while if an open-loop control law is used no such adjustment is possible.

In this section optimal control problems have been formulated for the determination of minimum cost enforcement policies. Although solutions to the mathematical problems were obtained, it should be pointed out that further work is necessary in order to obtain implementable policies. In addition to automating the data measurement to obtain an estimate of the state for any α, the optimal enforcement schedule for each blockside should be coordinated to determine a route for the officers issuing summonses. Some of the relevant concepts regarding routing were described in Section VII; the presence of daily feedback makes the problem more complicated and will probably necessitate the use of a computer aided routing procedure. Finally, the problem of noisy measurements (inaccurate measure of compliance) must be analyzed and the appropriate modifications in the optimal solution be carried out. The work in this section should be considered as the second step (the first is described in Section VII) in an effort to use system theory to improve the effectiveness of the officers assigned to enforce no-parking regulations.

SECTION IX

A LITTER GENERATION MODEL

INTRODUCTION

Since 1960 Systems Analysis techniques have been widely used in the study of various problems facing the metropolitan centers in this country. A survey of the literature, however, shows that the problem of litter in public places has received relatively little attention. In this section this problem will be analyzed using a simulation methodology called "System Dynamics" developed by Forrester[1].

The various ways in which litter is produced can be traced to one or more of the following primary factors: 1) Residential Population 2) Type of Land Use (other than residential) and 3) Pedestrian and Vehicular Traffic. Consequently, it was found convenient to divide the model into three broad sectors. Moreover, the above primary factors are assumed to be known and independent of each other. This assumption is justified since the time horizon of interest is short viz. of the order of a few weeks and the Data Bank for District Nine is expected to furnish the necessary information regarding these three factors (model inputs).

Litter in residential areas is generated mainly by the process of leakage of the wastes out of waste containers. This process can be called "indirect litter production" and is determined by various factors such as improper refuse packing, inefficient sanitation services, etc. Pedestrian traffic contributes to litter both by direct littering and indirect littering depending on several psychological factors[19]. Municipal authorities can exercise control over the amount of litter via enforcing regulations as well as efficient street sweeping. The above mechanisms are modelled in detail and the model behavior under alternative policies is examined in this section.

Thus, this model accepts as its input previously known or easily available data pertaining to the area under consideration and produces as its output the dynamic behavior of the litter as well as its spatial distribution over the area. The model is expected to serve as a valuable guide in suggesting better ways of keeping down the amount of litter in the streets.

LITTER PRODUCTION DUE TO RESIDENTIAL WASTE

The System Dynamics[1] approach to modelling focusses on the feedback structure of systems and the resulting mode of their dynamic behavior. System variables are classified into three general types. 1) Level Variables (denoted by a box) 2) Rate Variables (denoted by a valve) and 3) Auxilliary variables (denoted by a circle). Rate variables feed into or deplete Level variables. Levels, in turn, govern the Rates through Auxilliary variables, giving rise to circular relationships (Feedback loops). A feedback loop in which a change in one of the variables results in a further change in the same direction due to circular causality is called a positive feedback loop and is indicated by a (+) in the figures; on the other hand, if a change in a variable tends to be counteracted due to the circular causality, that loop is termed negative feedback loop and is indicated by (-) in the diagrams. Furthermore, the number of Level variables involved in a loop is the order of that loop. Such feedback loops, when coupled together, comprise the entire system. The dynamic behavior mode of the system is then determined by the signs and orders of individual loops as well as the way they are coupled.

With these preliminaries in mind, it would be helpful to look at the section of the model concerning the transformation of residential waste into litter in public places, depicted in Figure 27.

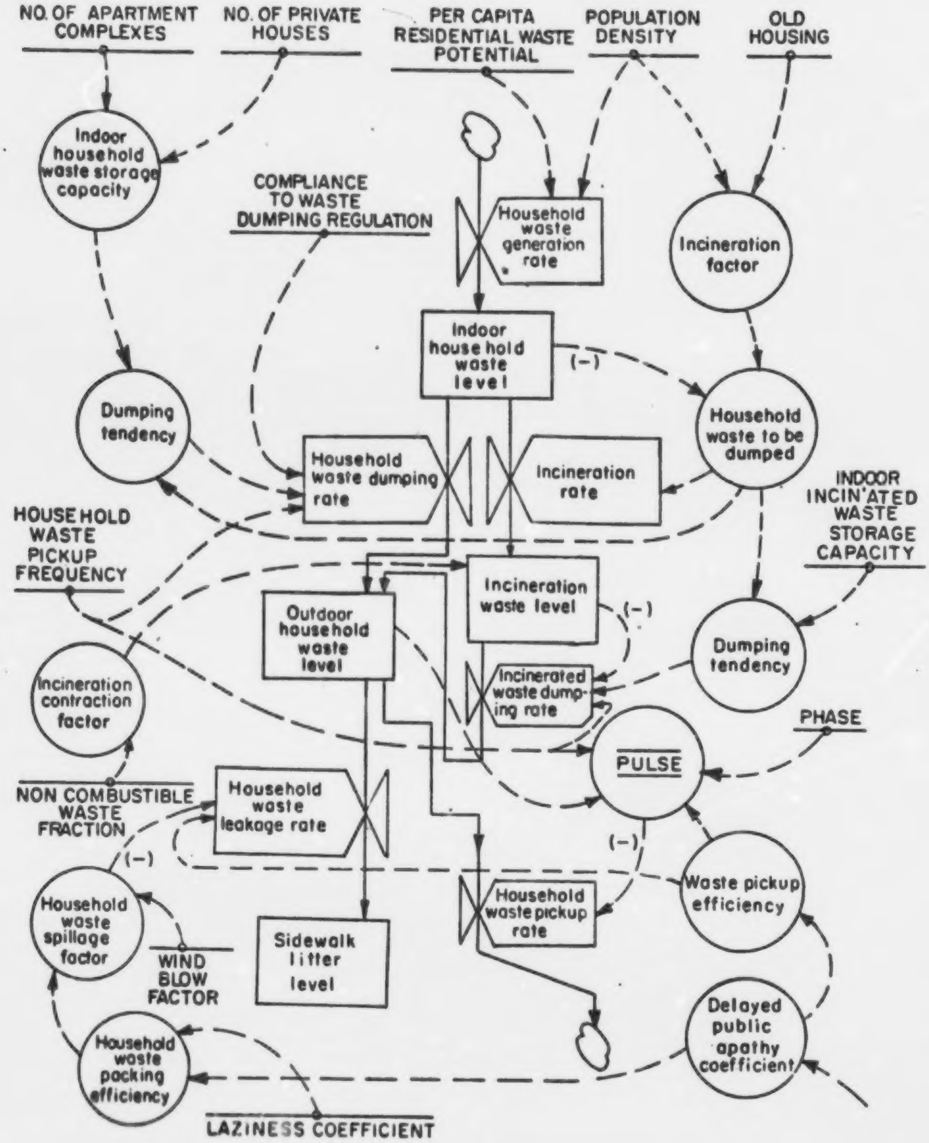
NO. OF APARTMENT COMPLEXES
NO. OF PRIVATE HOUSES
PER CAPITA RESIDENTIAL WASTE POTENTIAL
POPULATION DENSITY
OLD HOUSING
Indoor household waste storage capacity
COMPLIANCE TO WASTE DUMPING REGULATION
Household waste generation rate
Incineration factor
Indoor house hold waste level
(−)
Dumping tendency
Household waste to be dumped
Household waste dumping rate
Incineration rate
HOUSE HOLD WASTE PICKUP FREQUENCY
INDOOR INCIN'ATED WASTE STORAGE CAPACITY
Incineration waste level
(−)
Outdoor household waste level
Dumping tendency
Incineration contraction factor
Incinerated waste dumping rate
PHASE
PULSE
NON COMBUSTIBLE WASTE FRACTION
Household waste leakage rate
(−)
(−)
Waste pickup efficiency
Household waste spillage factor
WIND BLOW FACTOR
Sidewalk litter level
Household waste pickup rate
Delayed public apathy coefficient
Household waste packing efficiency
LAZINESS COEFFICIENT

Fig. 37. Litter generation due to residential waste

The rate of household waste production depends mainly on the population density. This dependence was modelled by assigning a certain waste potential for each person, a number that can be reasonably arrived at by collecting the required data and that is independent of the area under consideration. Furthermore, it was also assumed that the residential waste is generated only from food preparation and related activities that take place during the early afternoon and evening hours. This is believed to be a fairly accurate approximation to reality.

The household waste thus accumulated is either placed in refuse containers directly or first incinerated and subsequently placed in containers. The waste fraction that would be incinerated is clearly determined by the existence of the necessary equipment within buildings on the blockside under consideration. The following two facts can be used for estimating the available incineration facility.

1) There is a municipal law which makes it obligatory for landlords to install incinerators if the number of units in the building exceeds a certain threshold. Note that a high density of units also implies high population density.

2) Since the above law is a recent one, most of the old buildings do not have built-in incinerators. (The related information can be obtained from the housing department.) Figure28 results from the above two considerations. Thus, a very low population density implies a total absence of any incineration, followed by a linear increase in incineration factor depending on the percentage of old houses in the area - in the middle range of density. Finally, a density of 200 people per 100 feet or more in new housing implies incineration of all the waste that is produced. An important advantage of incineration is the reduction of the waste volume which depends, of course, on the amount of noncombustible material present in the waste.

Both incinerated and unincinerated (unprocessed or raw) wastes are placed on the designated external locations at rates that are functions of so-called 'Dumping Tendency' and 'Non-compliance to Household Waste Dumping

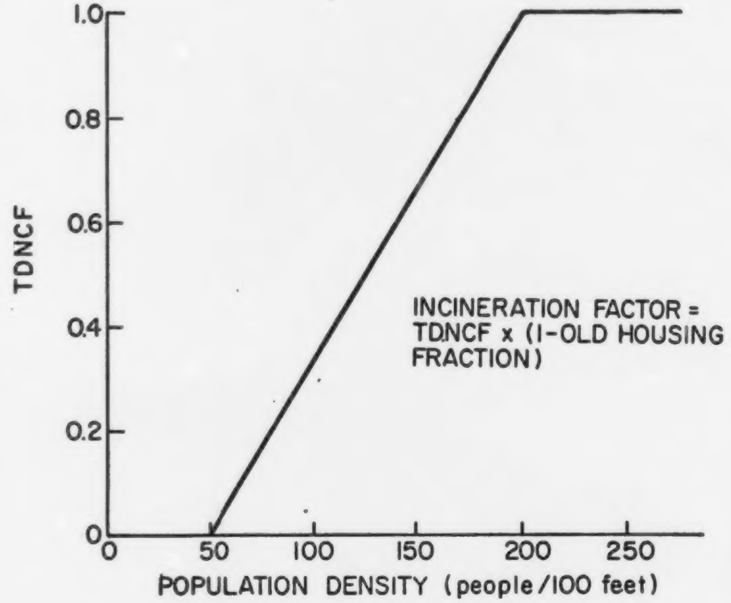

Fig. 28. Determination of incineration factor

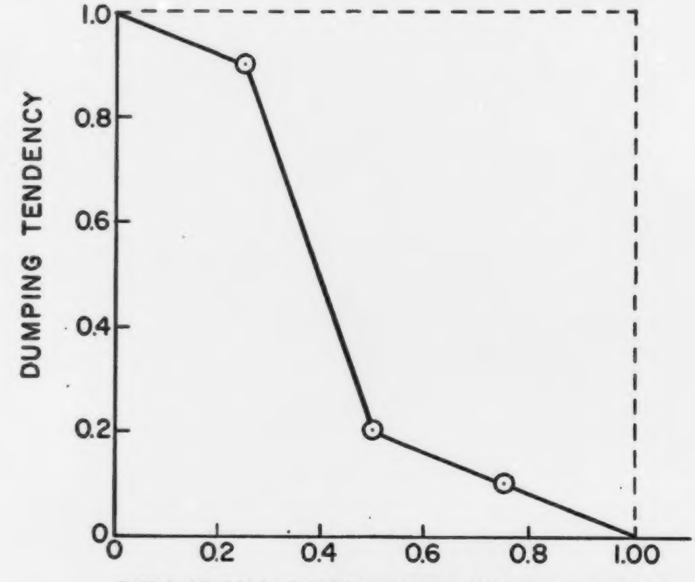

Fig. 29. Dumping tendency vs. waste storage capacity

Regulation'. The Dumping Tendency essentially characterizes a building superintendent or a house-owner and can be viewed as the probability that he will dump the accumulated refuse outdoors. The functional dependence of the Dumping Tendency has been assumed to be only upon the fractional storage capacity remaining indoors (Fig.29). The axes represent the ideal desired characteristic, while the dotted line represents a most unfavorable refuse dumping policy from the viewpoint of litter generation. The third curve represents a typical superintendent and has been actually used in the simulation. Two negative feedback loops (first order) of a nonlinear nature thus result tending to maintain the two waste levels at the respective waste storage capacities. Also, there is a sudden increase in the dumping rates during the period just preceding the time the sanitation truck is scheduled to pick up the waste. This could be represented by a Kronecker delta sequence. Clearly, the ideal waste dumping rate would be as shown in Fig. 30, but due to non-zero dumping tendency and non-compliance to regulations the actual dumping rate is as in Fig. 31.

The household waste stored in refuse containers on the blockside (ODHSWL) leaks to give rise to litter in the streets. The Leakage Rate is determined by the Spillage Factor (AHWSPF) which is defined as a fraction of the waste that leaks out in the period of one hour. The most important factors affecting the Spillage Factor are as follows:

a) Wind blow factor (WINBLF) - Represented in the model by a normal random variable with appropriate mean and variance.
b) Household waste packing efficiency (HPACEF) - This is modelled by a large constant component and a second component which is a linear function of the 'Public Apathy Coefficient' to be explained later.
c) Spillage tendency (SPT) - Defined as the Spillage Factor with normal values of (a) and (b). This depends upon the waste as shown in Fig. 32. It is also assumed that leakage takes place from the top layer of the waste in the containers.

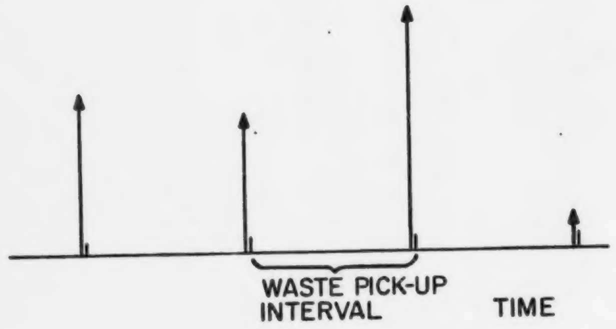

Fig. 30. Ideal waste dumping pattern

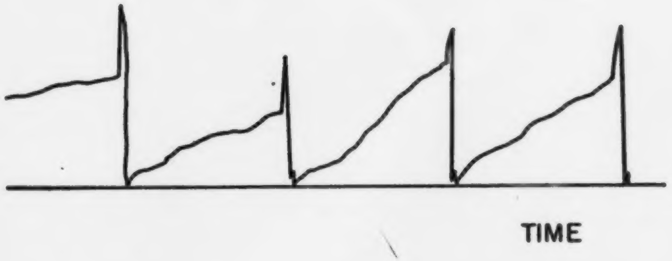

Fig. 31. Actual waste dumping pattern

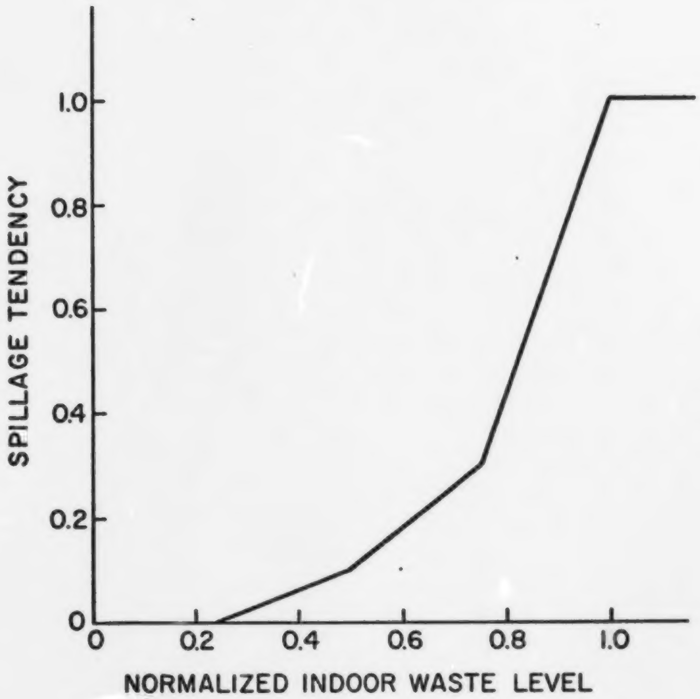

Fig. 32. Spillage tendency versus indoor waste level

For the waste in excess of the total container capacity, the spillage factor would clearly be independent of (c).

This leakage process is represented in the model as another negative feedback loop tending to maintain the Outdoor Waste Level constant. Notice, however, that the feedback effect is extremely small since the quantity leaking out is very small in comparison with the waste level.

Another significant cause of leakage is the lack of careful handling of the waste by the sanitation department personnel during its collection. This has also been attributed in part to the prevalent apathy among the general public.

This completes the description of the part of the model related to the residential waste. We now turn to the consideration of commercial waste.

LITTER PRODUCTION FROM COMMERCIAL WASTE

Refuse created by commercial establishments gives rise to litter in the same general way as does the residential waste described before (Fig.33). However, each of the six types (see figure) into which the commercial activities have been divided is different with respect to the values of the various parameters involved. For example, the waste potential and the indoor waste storage capacity of a restaurant and a department store are vastly different. Again, the packing efficiencies of an office and a store may also be different. Notice that creating separate levels for each of the above types will be redundant, since we are primarily interested in only the basic behavior modes of the model. The obvious and convenient compromise is to represent the commercial waste as a whole by just one level and then to average different parameters and use aggregate variables when appropriate.

The waste potential of supermarkets, restaurants and small shops has been assumed to be proportional to the area they occupy. The waste

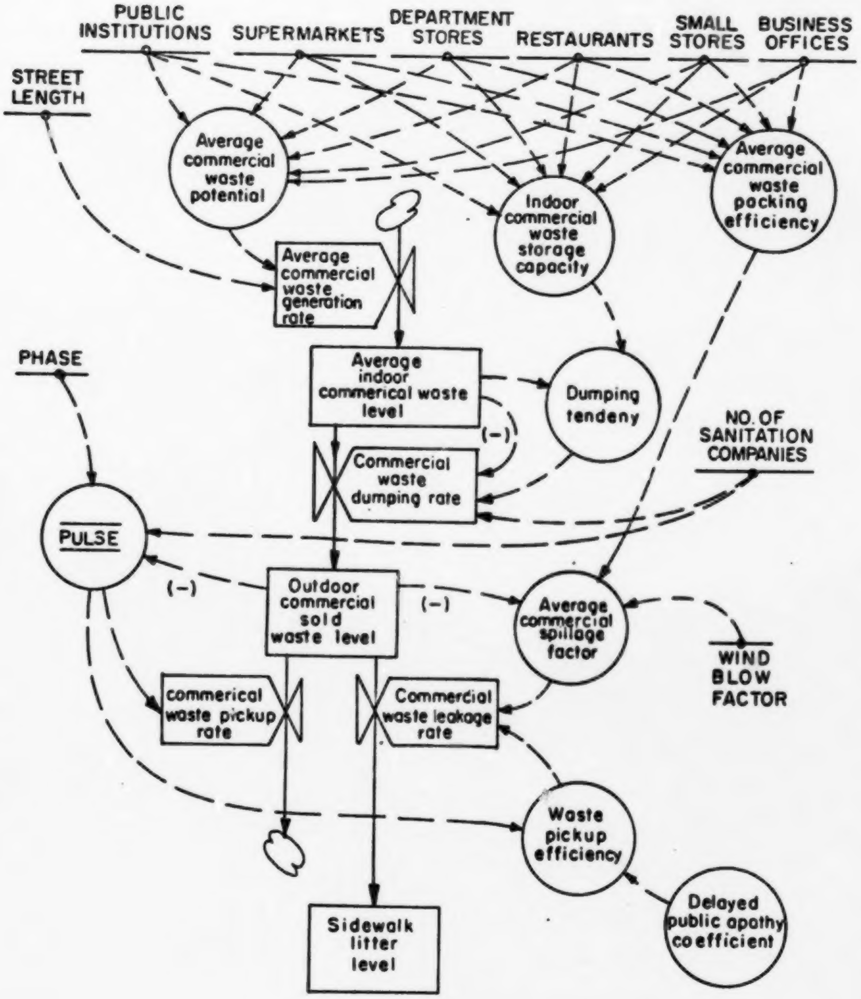
PUBLIC INSTITUTIONS
SUPERMARKETS
DEPARTMENT STORES
RESTAURANTS
SMALL STORES
BUSINESS OFFICES
STREET LENGTH
Average commercial waste potential
Indoor commercial waste storage capacity
Average commercial waste packing efficiency
Average commercial waste generation rate
PHASE
Average indoor commerical waste level
Dumping tendeny
(−)
Commercial waste dumping rate
NO. OF SANITATION COMPANIES
PULSE
(−)
Outdoor commercial sold waste level
(−)
Average commercial spillage factor
WIND BLOW FACTOR
commerical waste pickup rate
Commercial waste leakage rate
Waste pickup efficiency
Delayed public apathy coefficient
Sidewalk litter level

Fig. 33. Litter generation from commercial waste

potential of public institutions and business offices has been assumed to be proportional to the number of visitors and the number of employees, respectively. Finally, the waste potential of a department store is taken to be an intuitively appealing large number in comparison to institutions and business offices. Each of the waste potentials was modulated by appropriate time functions in order to reflect the variation in waste generation rates over a period of twenty four hours.

The Indoor Waste Storage capacities of the six kinds of commercial establishments have also been postulated as being proportional to the floor area they occupy. The total commercial waste (AINCMW) together with the total indoor waste storage capacity (NCMCAP) determine the Commercial Dumping Tendency (CDMT) in a way analogous to the determination of the Household Waste Dumping Tendency (see Figure 29). The Commercial Waste Dumping Rate (ACWDR) is the product of CDMT and noncompliance to Dumping Regulation (STNCMP). This completes another negative feedback loop in the model.

The commercial waste leakage process is similar to the Household Waste Leakage process. The Commercial Packing Efficiency is obtained by averaging the packing efficiencies of the six categories weighted by their respective waste potentials. Since the department stores are known to be efficient in handling their refuse by virtue of their financial and manpower resources, a high packing efficiency was assigned to them. In contrast, supermarkets and restaurants have a low packing efficiency due mainly to (a) the unmanageable nature of the waste they produce, e.g., leftover food, food packaging, miscellaneous grocery items, etc. as contrasted to the packaging materials which are the main items produced as refuse by department stores; and (b) the limited resources available to them.

Another problem peculiar to commercial areas was the presence of several private carting companies serving the area, each one of them with different schedules serving different stores. Due to the resulting complications and the difficulties foreseen in obtaining the relevant data,it was thought best to make the following simplifying assumption

Pick Up Interval = 168 hours/no. of sanitation companies .

The last, but not the least, source of litter is traffic.

TRAFFIC AS A SOURCE OF LITTER

A portion of the complete model pertinent to this section is shown in Figure 34 . Clearly, the most fundamental quantity here is the volume of pedestrian traffic at any given time. The traffic pattern as a function of time, repeating itself every day, is shown in Figure 35. The two peaks represent morning and evening rush hours, the valley represents afternoon lull. The actual volume of traffic is obtained by scaling up this traffic pattern by a factor which is a linear function of the number of public institutions, department stores, business offices, population density and public transportation stops in the given blockside. The multipliers appearing in this function are termed 'Traffic Intensity' of the corresponding quantity and can be determined from collected data.

Similarly, the various commercial activities contribute to the waste potential of a pedestrian as well. These contributions are termed 'Waste Intensity' of the corresponding quantity. For instance, the Waste Intensity of a snack-shop or an ice cream parlor is much higher than that of a business office. We can then simply write,

Traffic Waste Potential =
Pedestrian Traffic Volume x Pedestrian Waste Potential

The fraction of Traffic Waste Potential that is actually transformed into litter is defined as the Littering Tendency Multiplier (LTM) of the public. It can also be interpreted as the probability of an individual pedestrian being a litterer (assuming that the number of pedestrians is large).

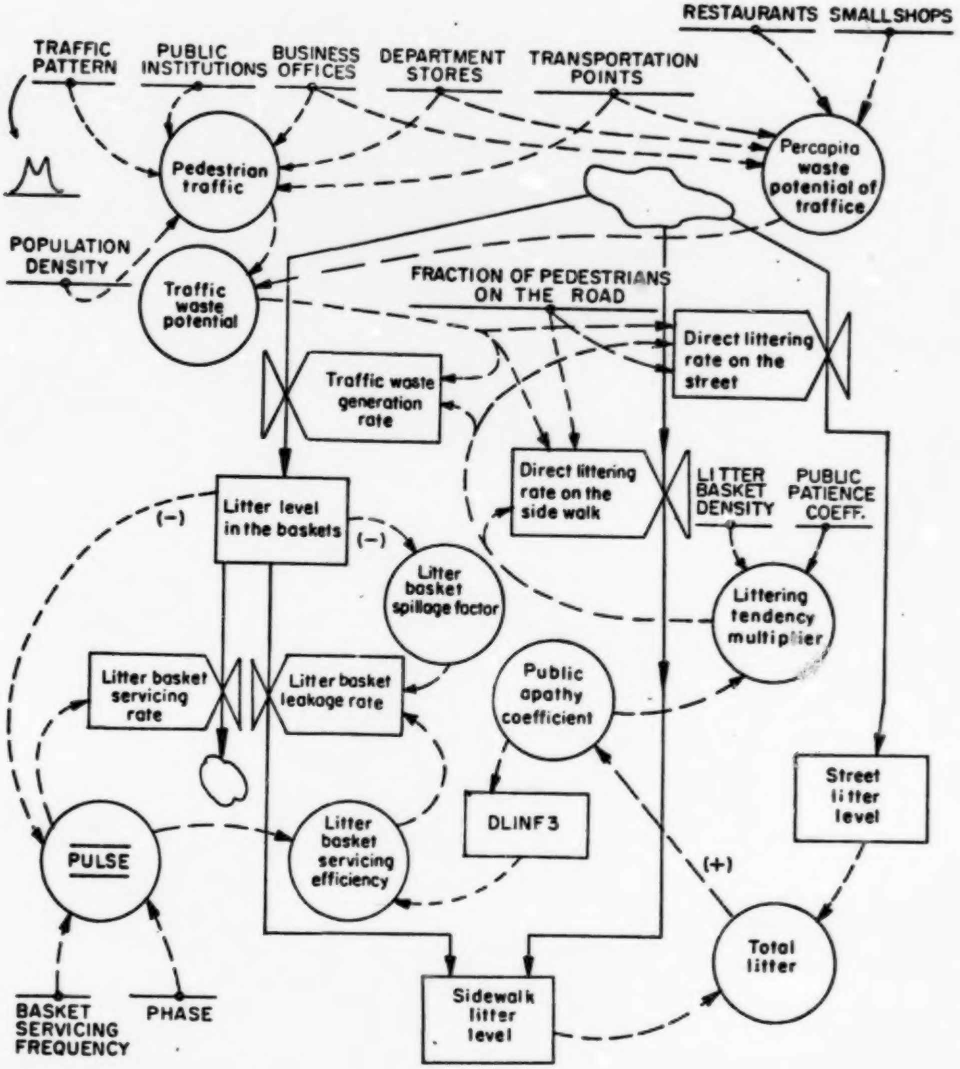
RESTAURANTS
SMALLSHOPS
TRAFFIC PATTERN
PUBLIC INSTITUTIONS
BUSINESS OFFICES
DEPARTMENT STORES
TRANSPORTATION POINTS
Pedestrian traffic
Percapita waste potential of traffice
POPULATION DENSITY
Traffic waste potential
FRACTION OF PEDESTRIANS ON THE ROAD
Direct littering rate on the street
Traffic waste generation rate
Direct littering rate on the side walk
LITTER BASKET DENSITY
PUBLIC PATIENCE COEFF.
Litter level in the baskets
(−)
(−)
Litter basket spillage factor
Littering tendency multiplier
Litter basket servicing rate
Litter basket leakage rate
Public apathy coefficient
Street litter level
DLINF3
PULSE
Litter basket servicing efficiency
(+)
Total litter
BASKET SERVICING FREQUENCY
PHASE
Sidewalk litter level

Fig. 34. Litter generation due to traffic

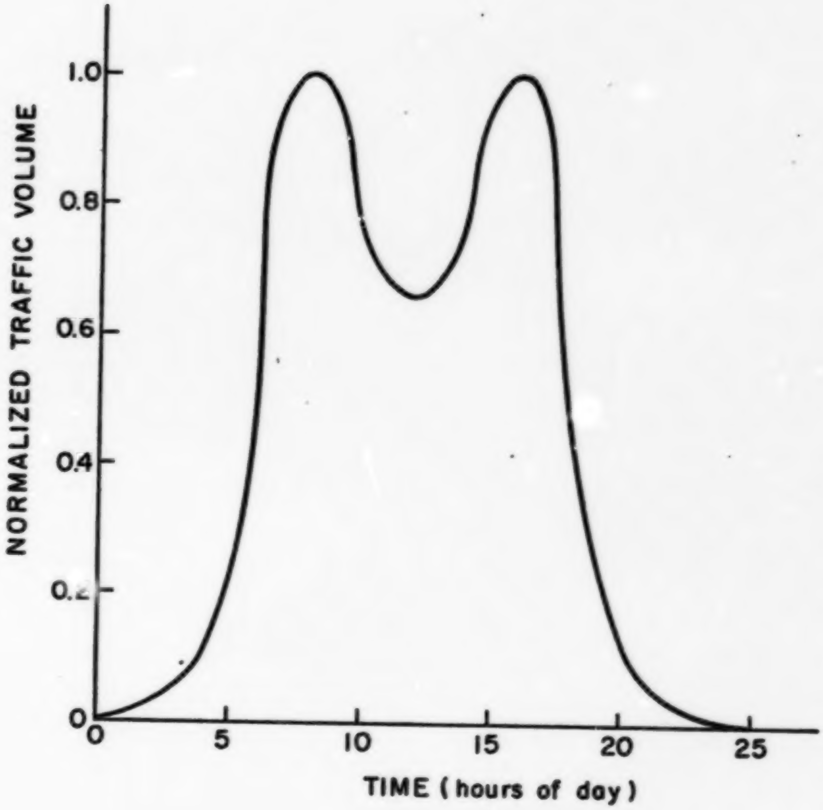

Fig. 35. Assumed daily traffic pattern

Clearly, the Littering Tendency Multiplier is the result of interplay between a variety of factors reflecting public psychology vis-a-vis litter in the streets. However, we have chosen to isolate and quantify only two of these factors believed to have a maximum effect on the littering tendency of the public.

1) Public apathy coefficeint (PAC) - This coefficient is a measure of indifference on the part of the public in general towards cleanliness of public places in the city; thus a value of one implies a total public disregard towards the environment, while a value of zero represents completely conscious and watchful pedestrians. The exact value of this coefficient is again dependent upon several factors. Nevertheless, recall that our time horizon of interest extends to only a few weeks, a period of time over which factors such as public education, economic conditions, etc. cannot change appreciably and hence can be assumed to be constant. Consequently, the amount of litter itself present in the streets is the only important determinant of public apathy, other factors being constant. Figure 36 shows the postulated relationship which can be said to approximate reality under a fairly wide class of conditions. Thus, if the streets are quite clean, the people tend to keep them that way by becoming more vigilant; if the streets are not clean, the people become naturally apathetic since the attitude 'what difference is one more piece of paper going to make?' prevails. However, 'intolerably dirty' streets have an awakening effect on the public, again tending to make them aware. The current public awareness of environmental problems may be cited as an example of this effect. Finally, notice that the relationship between public apathy and total litter in the streets constitutes the most important link in the feedback path of the major positive feedback loop in the model.

2) Public patience coefficient (PPC) - Public patience clearly depends on a large number of factors, outside the realm of this model, in very obscure ways. Hence it was deemed best to represent it as a normal random variable with a mean of 0.5 and appropriate variance. Only values

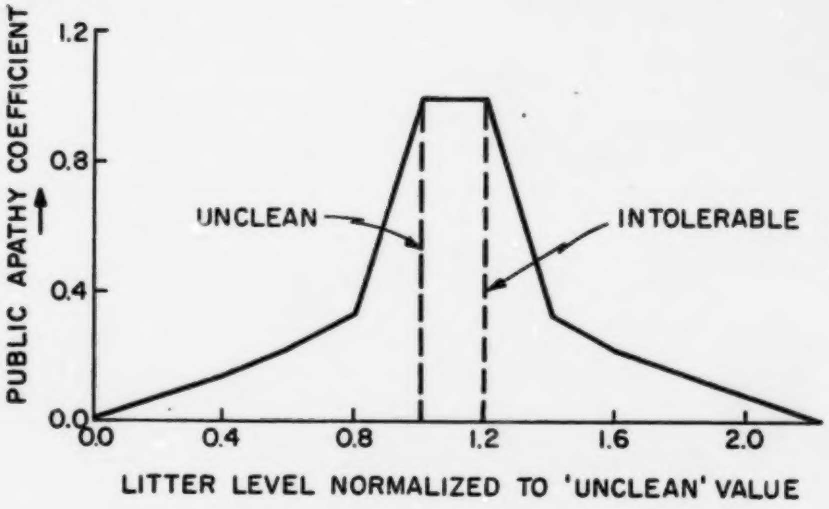

Fig. 36. Public apathy versus litter level

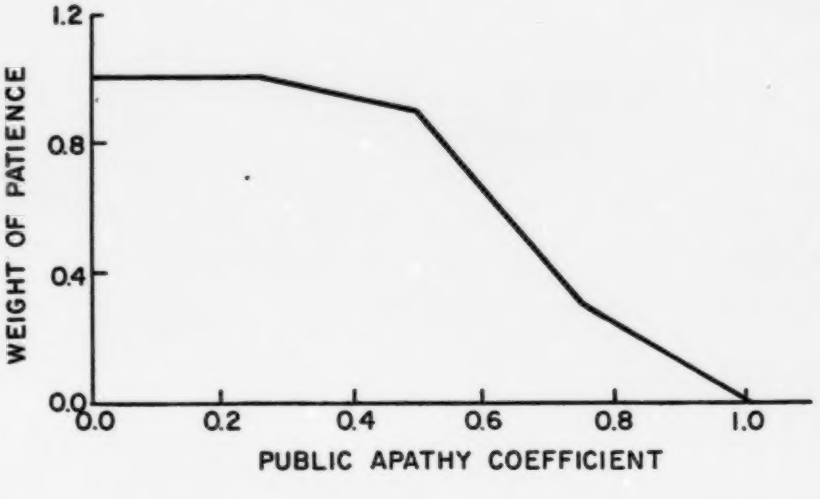

Fig. 37. Public patience weighting function

lying between zero and one are accepted. (The choice of a normal random variable was also prompted by programming considerations.) On the other hand, the effect of public patience on public littering tendency may be said to be governed by two factors. a) Litter Basket Density - e.g. a good degree of public patience must be accompanied by at least a reasonable number of litter baskets on the street to get a low littering tendency. Conversely, even an impatient public will have a low littering tendency if baskets are readily available. b) A weighting factor that in turn depends on public apathy as depicted in Figure 37. The implication is that the patience of an individual becomes an important factor only if he is aware of the effects of litter in the first place. On the other hand the question of patience does not arise for a person with total disregard towards his environment.

As a result of the above considerations, the following two rates are obtained:

Direct Littering Rate =
Traffic Waste Potential x Littering Tendency Multiplier

Traffic Waste Generation Rate =
Traffic Waste Potential x (1-Littering Tendency Multiplier)

The latter accumulates into 'Litter Level in the Litter Baskets'. Leakage from litter baskets takes place by a similar mechanism as described earlier with Packing Coefficient equal to zero. Also note that in the situations when the baskets are full then

Direct Littering Rate = Traffic Waste Potential

Traffic Waste Generation = 0

without regard to other factors.

It is important to notice that the Delayed Public Apathy Coefficient

(DPAC) is the result of passing PAC through a third order filter with a delay of about 2 days. This is so because PAC represents immediate reaction of an individual to the litter while DPAC is a delayed reaction and hence would fluctuate to a lesser extent.

DYNAMICS OF THE GENERATED LITTER

Total litter consists of sidewalk litter and street litter. The leakage processes described in the previous sections and also a major portion of the Direct Generation Process accumulate into Sidewalk Litter Level.

The Sidewalk Sweeping Factor (SWF) may be defined as the fraction of the total length of sidewalk that is being swept at any given time. SWF has been taken to be a linearly decreasing function of DPAC with full sweeping for DPAC=0 and no sweeping activity for DPAC=1. With these definitions, it is clear that more sidewalk litter implies higher sweeping rate and vice versa; hence the negative feedback loops shown in Figure 38.

Furthermore, the fraction of sweeping activity which can be called illegal - sweeping the sidewalk litter on to the street is contrary to municipal regulations - is assumed to be determined by the degree of laziness of the sweepers. Like patience, laziness is a very uncertain human characteristic and consequently has been modelled as being random. Lastly, litter on the portion of the sidewalk left unswept is blown by the wind on to the street (WBLR).

The street litter thus generated is depleted periodically by mechanical street sweeping and flushing. The street sweeping operation is obstructed by the presence of illegally parked cars whose number depends on the parking enforcement policies. The exact nature of these effects has already been treated in previous sections. In this case it was chosen to be a first order delay effect with a delay of 24 hours.

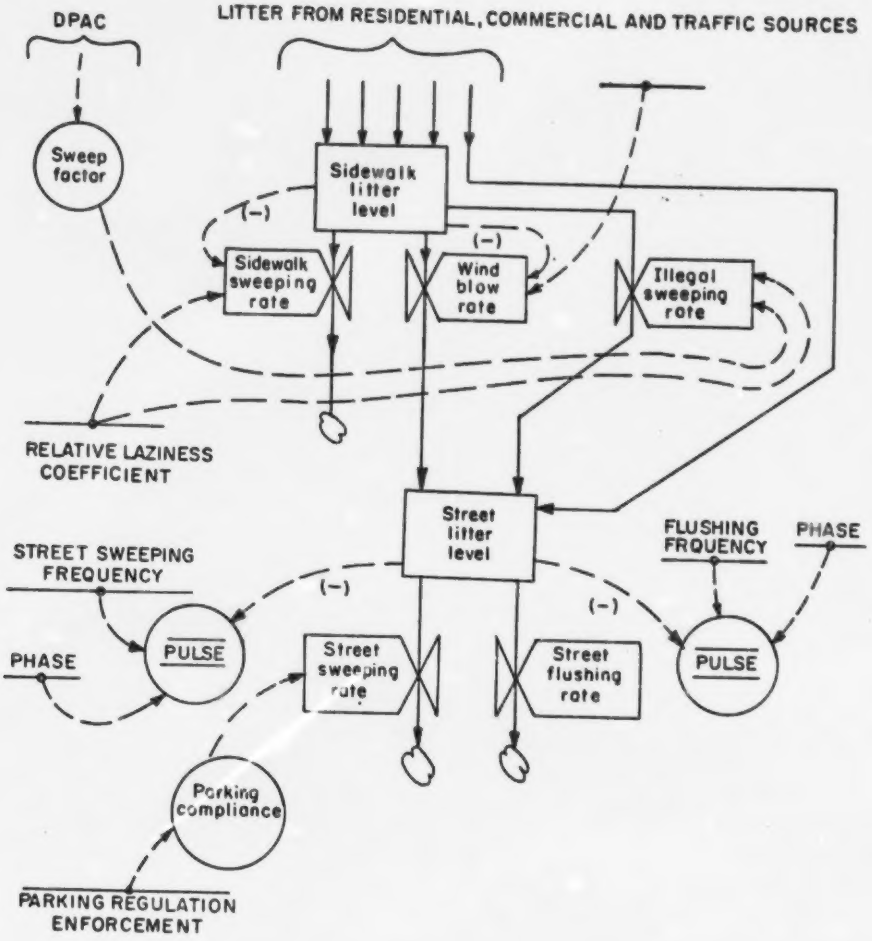
DPAC
LITTER FROM RESIDENTIAL, COMMERCIAL AND TRAFFIC SOURCES
Sweep factor
Sidewalk litter level
(−)
(−)
Sidewalk sweeping rate
Wind blow rate
Illegal sweeping rate
RELATIVE LAZINESS COEFFICIENT
Street litter level
STREET SWEEPING FREQUENCY
FLUSHING FRQUENCY
PHASE
(−)
(−)
PHASE
PULSE
Street sweeping rate
Street flushing rate
PULSE
Parking compliance
PARKING REGULATION ENFORCEMENT

Fig. 38. Movement of the generated litter

MODEL SENSITIVITY TESTING

In order to evaluate the performance of the model and to test its behavior with respect to various parameters, it was thought best to define the following performance indices on the model.

1) Average litter level (A) - Defined as the sum of the Total Litter Level evaluated on each hour divided by the total number of hours that make up the period under consideration.

2) Fractional excess litter duration (X) - Defined as the fraction of the total period for which the Total Litter Level (TLL) exceeds a certain tolerable limit which has been taken to be 3 cu. ft. per 100 ft. of street length (TOLTLL).

2) Fractional low litter duration (W) - Defined as the fraction of the total period for which the Total Litter Level remains below a satisfactory limit which has been chosen to be 1 cu. ft. per 100 ft. of street length (SATTLL).

Each of the parameters, which can be characterized as control variables, was then varied over a feasible range of values and the behavior of the three performance indices was plotted. The above procedure was carried out for residential and commercial areas separately. The results of such tests are shown in Figures 39 through 45 . In passing, we claim that the above methodology for testing large and complex dynamic systems is superior to the one followed by Forrester[1] in that it is easier to interpret the results and draw conclusions from them.

Figures 39a and b depict the effect on litter of refuse storage capacity on the blocksides in residential and commercial areas, respectively. The average litter, curve A, undergoes approximately the same total change in both cases. However, curve A exhibits a sharp break in commercial areas,

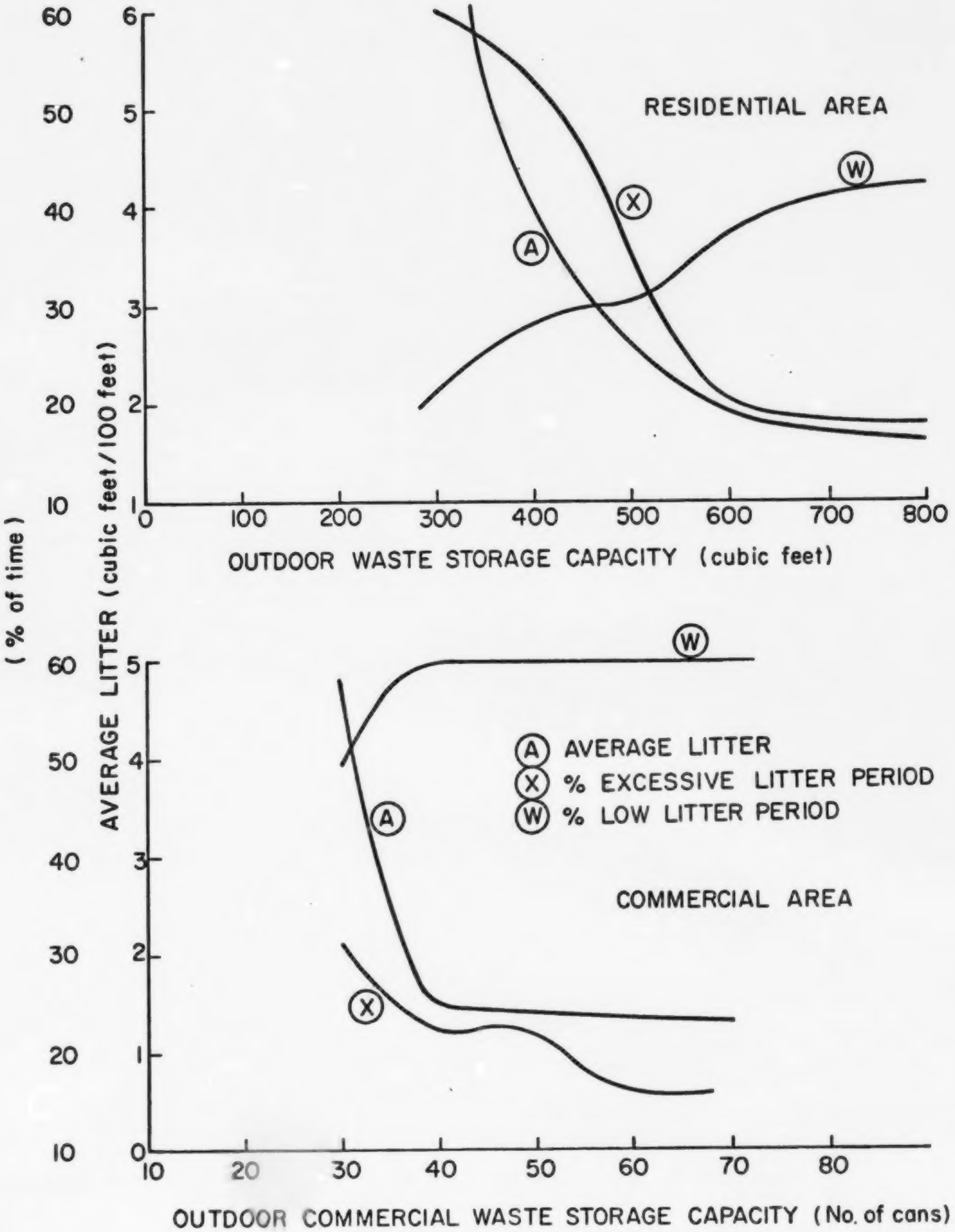

Fig. 39. Effect of outdoor waste storage capacity on litter
(a) Residential; (b) Commercial

while it is relatively smoother in residential areas. Curve X shows a much smaller change in commercial areas. All three curves settle down to their final values more quickly in Figure 39b.

In Figures 40a and b all three curves are far more sensitive to changes in the number of litter baskets in commercial areas than in residential areas, due to a much larger volume of traffic in the former.

Similarly, the frequency of emptying the litter baskets also affects commercial area litter to a larger extent as seen from Figures 41a and b (note the difference in scales). From Figure 41b it is clear that the average litter experiences exponential increase while the excess litter, curve X, and the satisfactory litter, curve W, duration show monotonic behavior with a considerable flatness in some regions.

However, the commercial area litter performance indices behave in an abnormal fashion (see Figure 42) when the number of private carting companies increases beyond a certain point. This is so because the effect of inefficient waste pick-up (i.e. spillage during pick-up) overwhelms the decrease in leakage resulting from more frequent emptying of waste cans. This is possible due to the large volume of waste generated in commercial activities. Infrequent refuse pick-up in residential areas affects the average litter adversely, as expected (Figure 43).

The frequency of street sweeping operation affects average litter mainly in the residential areas (see Figures 44a and b). We observe, however, in Figure 44a that over the range of 72-100 hours an increase in street sweeping interval increases the period for which litter is satisfactory, an apparent anomaly. This behavior can be explained by noting that an increase in sweeping interval in this range implies that sweeping instants come closer to the instants when parking compliance is highest, thus overwhelming the bad effects of lower sweeping frequency.

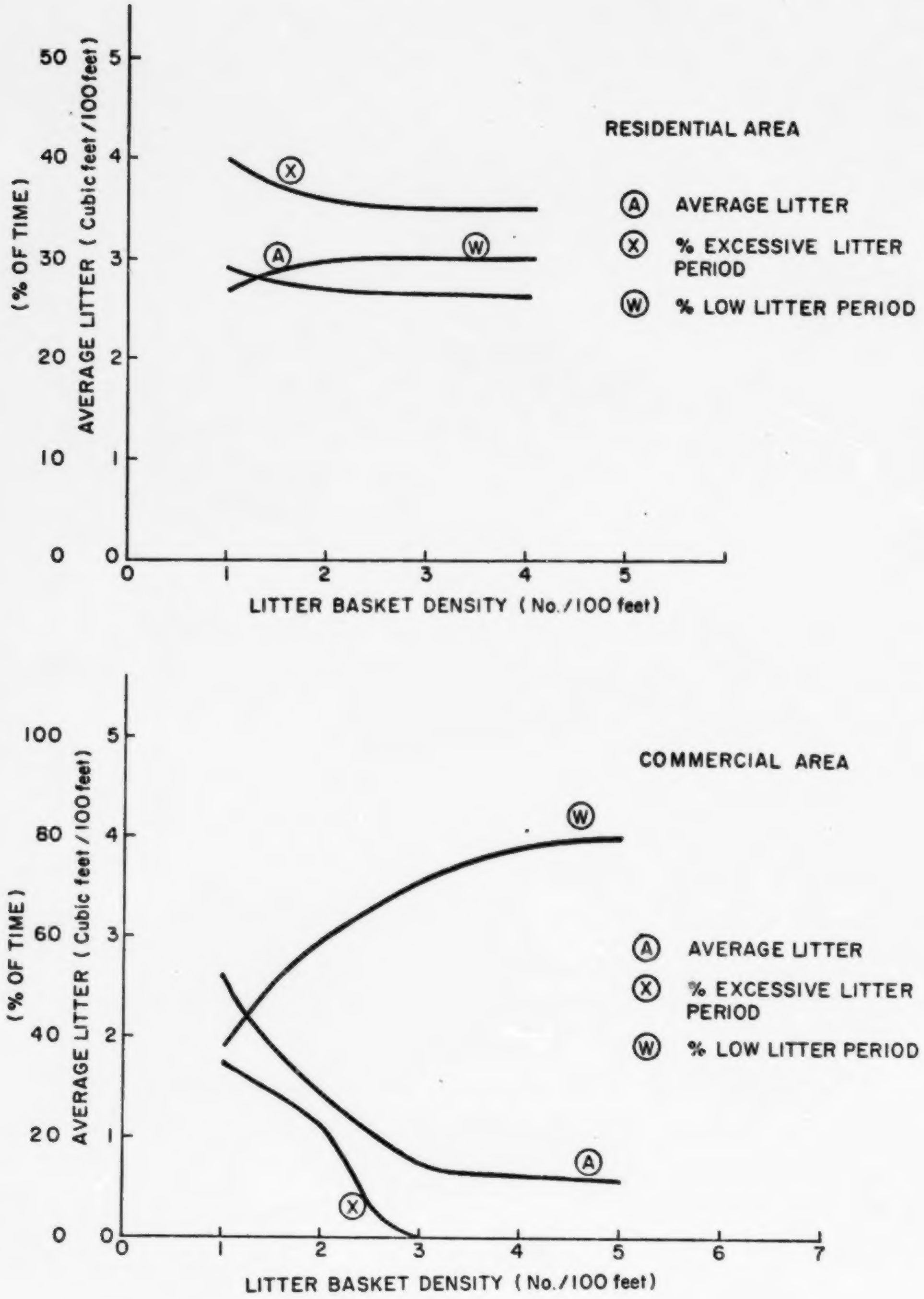

Fig. 40. Effect of litter basket density on litter
(a) Residential; (b) Commercial

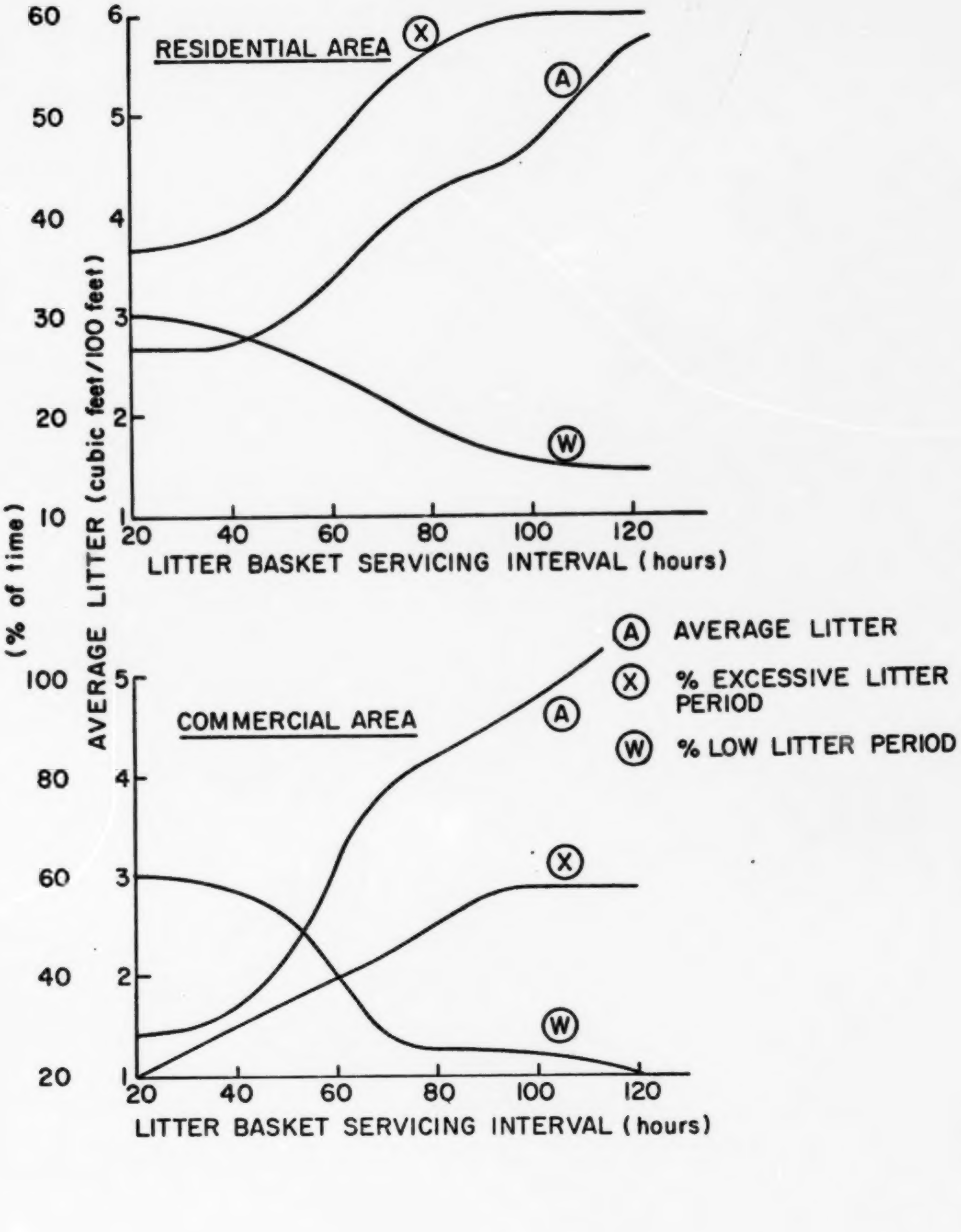

Fig. 41. Effect of frequency of litter basket servicing on litter (a) Residential; (b) Commercial

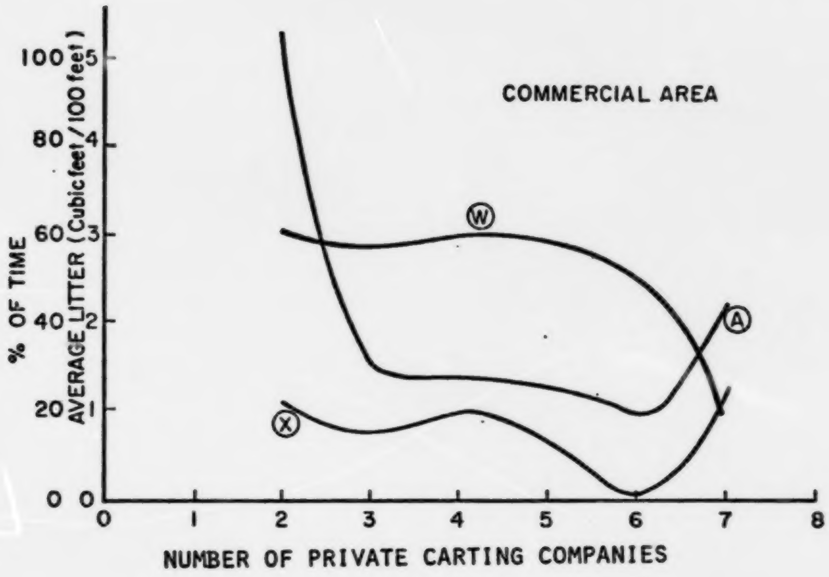

Fig. 42. Effect on litter of private carting companies

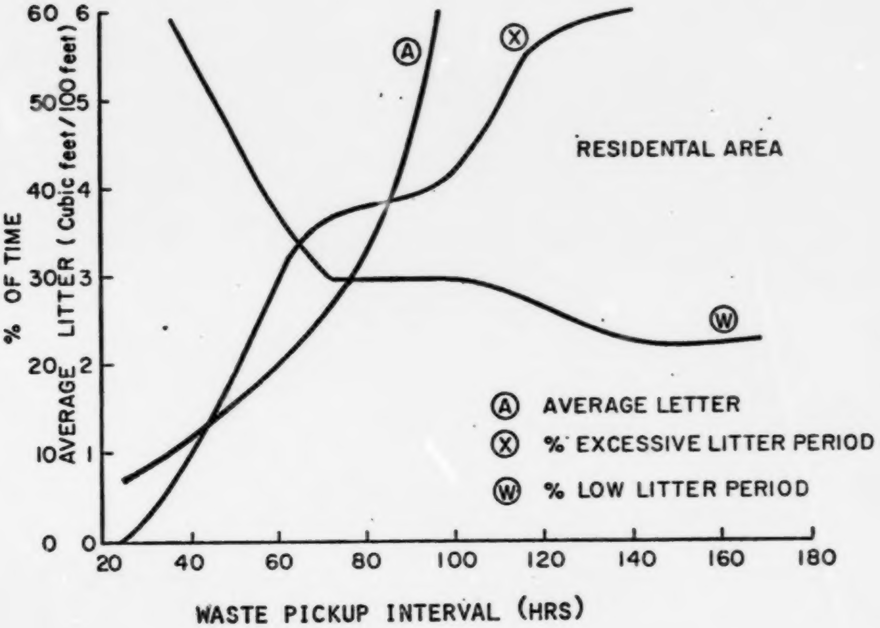

Fig. 43. Effect of residential waste pickup interval on litter

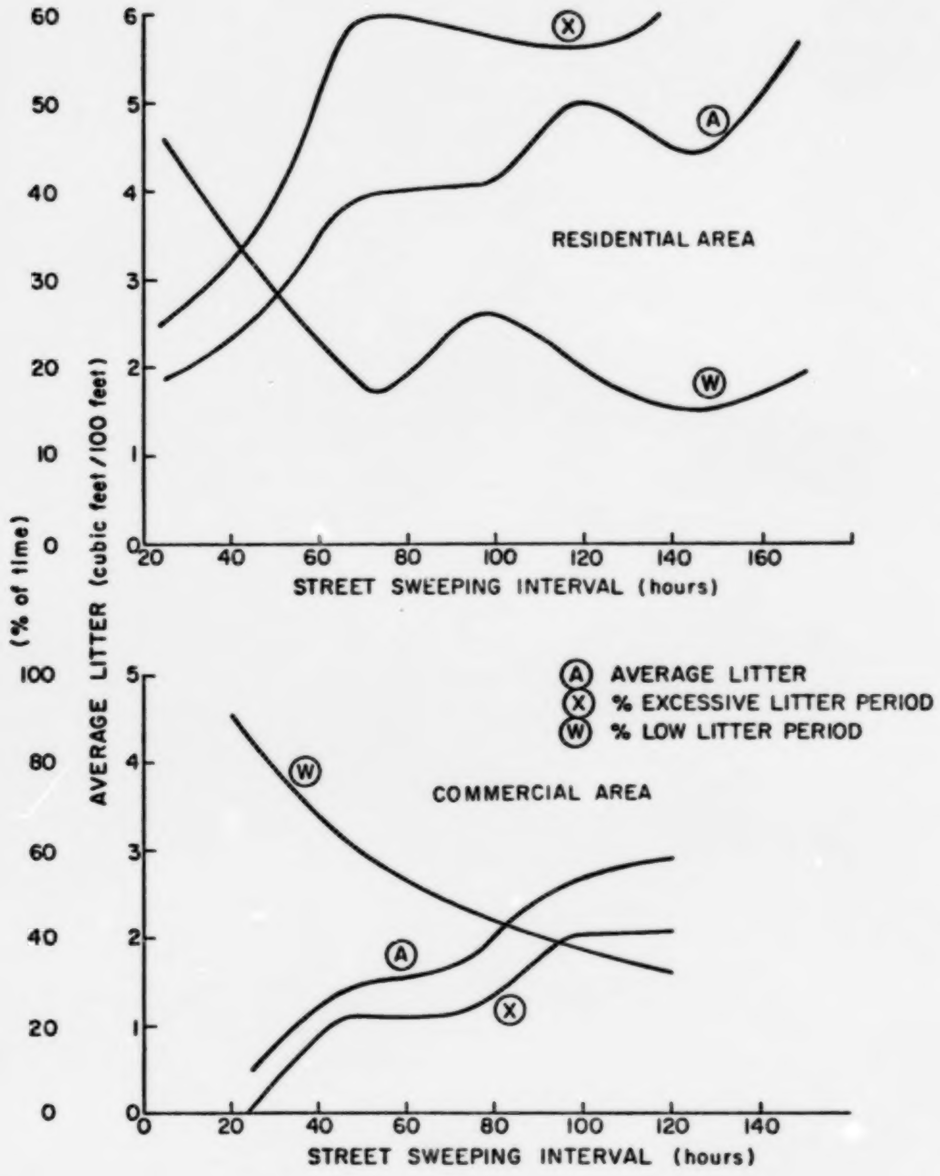

Fig. 44. Effect of street sweeping interval on litter
(a) Residential; (b) Commercial

It is also possible to improve the litter performance through only a shift in sweeping schedules (but maintaining the same sweep frequency) as is clear from Figures 45a and b.

On the basis of simulation results and parameter studies, the following general conclusions can be drawn:

I. Since commercial areas have a much larger volume of traffic, its effect is much stronger. Hence litter in commercial areas exhibits a highly dynamic behavior compared to that in residential areas. This is so because the effect of this feedback on the litter generated by traffic is immediate, whereas its effect on other sources of litter is delayed (DPAC) or, alternatively, dampened.

II. The average litter of a commercial area is more sensitive to parameters that affect the generation of litter (e.g. litter basket density, litter basket pick-up interval, etc.) and less sensitive to parameters that affect the removal of already generated litter. On the other hand, residential area average litter is more sensitive to parameters that affect the removal of the generated litter and vice versa. It follows that efforts towards keeping the streets clean should be directed towards preventing the litter generation in commercial areas and towards removal of litter in residential areas.

III. The choice of the particular parameter to be varied depends on several considerations such as the performance index one is interested in, location of the present operating point (whether it is on the steep or flat portion of the particular curve), the actual cost of varying that parameter, and so forth.

REMARKS

An important consideration in modelling large and complex social systems such as the one we have considered is that the inputs to the model

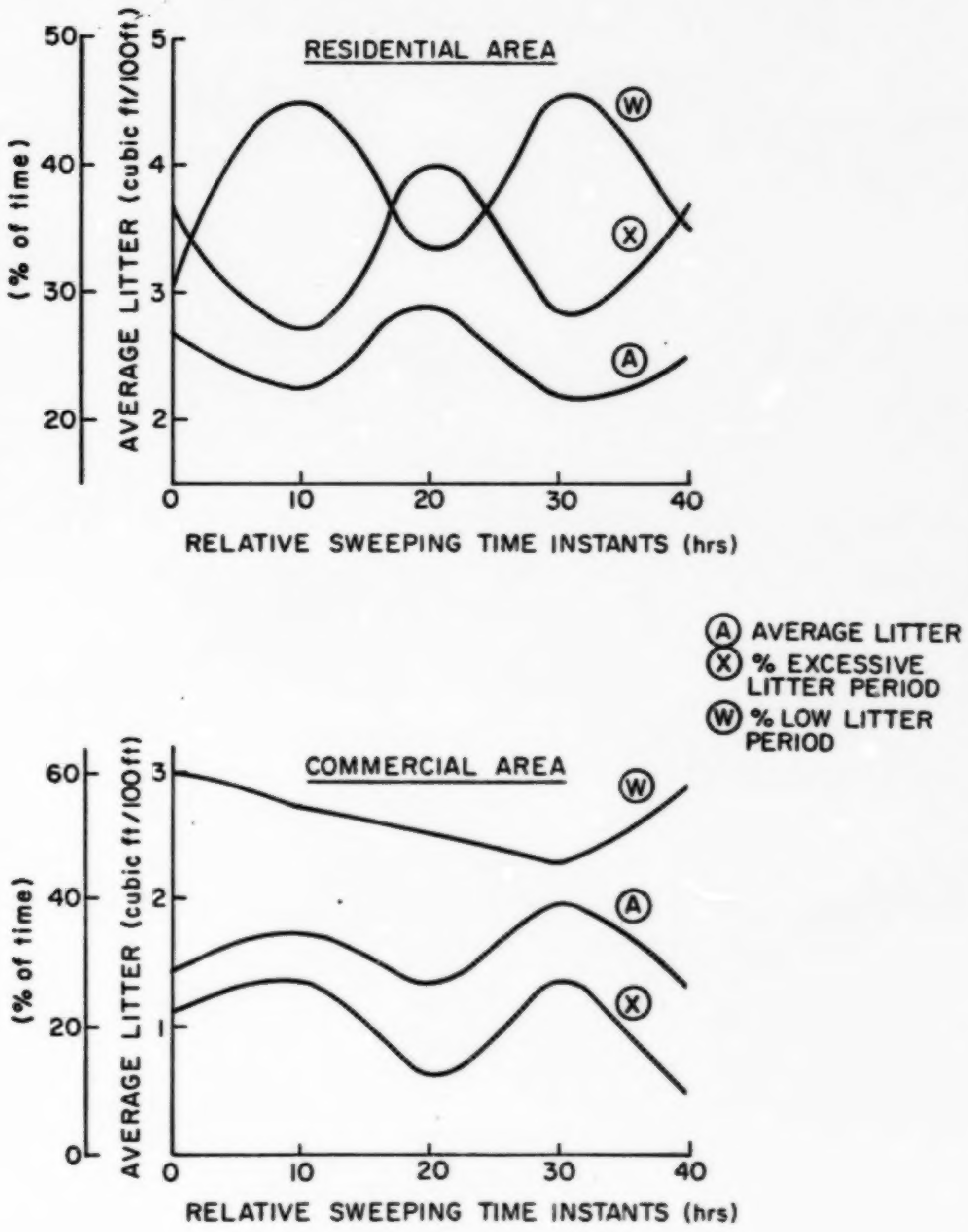

Fig. 45. Effect on litter of coordination between waste pickup and sweeping schedules

(a) Residential; (b) Commercial

represent quantities that can be easily measured and manipulated. This consideration is especially important during the process of model validation and its subsequent application as an aid to improving the real system. The following validation procedure constitutes the natural next step in the determination of a useful litter generation model.

1) For each blockside in the experimental district obtain from the computer data bank the required input quantities such as population density, composition of commercial activity, land use, street sweeping interval, etc. Litter volumes could then be measured from time to time using the procedure described in Section X. The model parameters and tabular relationships would then be adjusted so that the model output conforms to these figures over a time span of, say, one month.

2) Policy alternatives can then be tested, as suggested by Figures 39 through 45, to check whether the actual performance does indeed improve.

After these steps are carried out, one is ready to use the model safely in any situation.

Another interesting possibility seems to be the development of a computer program that manipulates the input variables of our model so as to reach an optimum. It may also be possible to superimpose various policy implementation costs as constraints on the model, so that an optimum thus obtained would be a feasible optimum.

The research presented in the next Section was designed to serve a dual purpose. First, to provide a simple, rational procedure for assessing street sweeping requirements and thus determine one of the basic inputs to a computerized routing procedure and, second, to obtain data for validating the model for litter generation presented in this section.

SECTION X

EXPERIMENTAL LITTER EVALUATION

In order to establish the level of cleanliness of the district's streets and thus determine the extent to which sweeping must be done, each and every one of the 1169 blocksides of District 9 was inspected and litter data were collected. Two basic measurements were taken for each curbside. For the first quantity, which represented the extent the blockside was littered, a one digit code was used.

Table 12. CODE FOR EXTENT OF LITTER

Code	Description
1	0-15% of blockside covered with litter.
2	15-40% " " " " "
3	40-100% " " " " "

The scale is not linear so that differences at low litter levels can be accentuated. The second quantity was an estimate of the physical size of the litter present along the curb.

Table 13. CODE FOR LITTER SIZE

Code	Description
1	Small pieces of paper (candy wrappers, crushed cigarette packs), cigarettes and other small objects.
2	Cans, bottles, milk cartons, etc.
3	Large objects such as tires, cartons, tree branches, etc., that cannot be swept by the mechanical brooms.
9	Code indicates special circumstances such as inaccessibility of the blockside due to construction, or lack of space for maneuvering, or dead end.

The length of curb in the district that had to be rated (103.6 miles) necessitated the use of several data collection teams. Each team consisted of the car driver, a navigator, and a data recorder. Prior to each field trip the navigator drew on a map the route to be followed so that specific blocksides would be observed just before being swept. The data sheet was prepared by converting the map route into a sequence of blocksides defined by their respective street boundaries. The data sheet included columns for entering the coded information on curb litter and litter size. In addition, the level of compliance to parking regulations, the existence of double parking and special traffic situations were also noted. Finally, provisions were made for entering comments such as the existence of a construction site or a service station. A typical section of a data sheet is shown in Figure 46.

During the survey the navigator would direct the driver along the predetermined route. Both the driver and the navigator would measure compliance, observe traffic, count the number of double parked cars, and relate the information to the data-recorder in the back seat. It was the responsibility of the latter to observe each curbside and rate it in accordance with the scales defined in Tables 12 and 13. If the other members disagreed with the data collector's assessment of the level of cleanliness of the curb, then this was also noted on the data sheet, unless consensus was obtained. In order to minimize such occurrences and establish a common reference for all members of the several teams, many photographs were taken of curbs with varying amounts of litter and with litter of different sizes. From the large set of photographs six were selected as being representative of each of the code values described above. Then all persons associated with data collecting had to rate the same predetermined route in the Brooklyn Central Business District. The results of that survey were analyzed and compared with the reference set of photographs. This was essentially a "calibrating" procedure (repeated several times during the period of data collecting) that attempted to decrease the variance in measurements by different observers.

BLOCKSIDE	LITTER SIZE 1 2 3	CURB RATING 1 2 3 4	COMPLIANCE	DOUBLE PARKED YES ✓	TRAFFIC YES ✓	PAGE NUMBER 1 of 5 . DATE 11/18/71 COMMENTS
ON RIVERSIDE BET. 160 161	2	2	100%			
ON RIVERSIDE BET. 161 162	2	1	100%			
ON 162 BET. FT WASH+RIVER	2	3	60%	✓	✓	construction
ON 162 BET. FT. WASH+BROAD	1	2	40%	✓		leaves
ON 162 BET. BROAD+AMSTER	1	1	100%			

Figure 46. Sample data sheet

Blocksides were surveyed just prior to being swept. This ensured that there would be maximum litter accumulation. During the months of October and November curbs in tree lined streets were covered with fallen leaves. Because the existence of these leaves is a seasonal phenomenon and because leaves are collected by special trucks, their presence was not taken into consideration in the coded litter rating. However, a note was made on the data sheet.

A second source of error in the measurement could be the effect of rain.

Heavy rain flushes and thus cleans the curb from small and medium size litter. Consequently, data were taken only if it had not rained for at least one week prior to each survey. Finally, no data were collected when snow was present or immediately after snow removal.

After the data had been collected, the street names and numbers were converted to the corresponding four digit blockside code number. The coded information was then entered into the computer data bank.

The next step in the procedure to evaluate the litter data was the conversion of the coded litter rating to a litter generation rate. An experiment was designed the purpose of which was the determination of litter density (measured in cubic feet of litter per one hundred feet of curb length) corresponding to each one of the nine two-digit litter ratings.

Random blocks were rated using the procedure described earlier. Care was taken to have a sufficient number of blocksides for each one of the nine ratings. Then the litter was swept by project members using hand brooms into a container and its volume measured. The length of curb actually swept depended on how much litter was needed to get a measurable quantity. In general, more curb length had to be swept in clean blocksides than in dirty ones. The actual length swept was then measured. The volume of litter, measured in cubic feet, divided by the corresponding length of swept curb, measured in fractions of 100 ft., yielded litter density in cubic feet per 100 ft. of curb. The results of the experiment are shown in Table 14.

At least six samples were taken for each rating except for the 1-3 case for which no samples could be found. The average value was the one associated with each litter rating. The results of Table 14 are also presented in Figures 47 and 48.

In Figure 47, the ratings have been grouped according to the first digit

Table 14 . BLOCKSIDE RATINGS AND VOLUME OF LITTER

Blockside Rating	No. of Samples	Expected Value Cu. ft./100 ft.	Variance	Stand. Dev.
1-1	9	0.027	0.00038	0.019
1-2	6	0.321	0.0017	0.041
1-3	0	-	-	-
2-1	6	0.249	0.0052	0.072
2-2	6	0.645	0.0243	0.156
2-3	6	1.24	0.0342	0.185
3-1	6	0.628	0.0355	0.188
3-2	7	2.12	0.272	0.52
3-3	6	3.03	0.4536	0.67

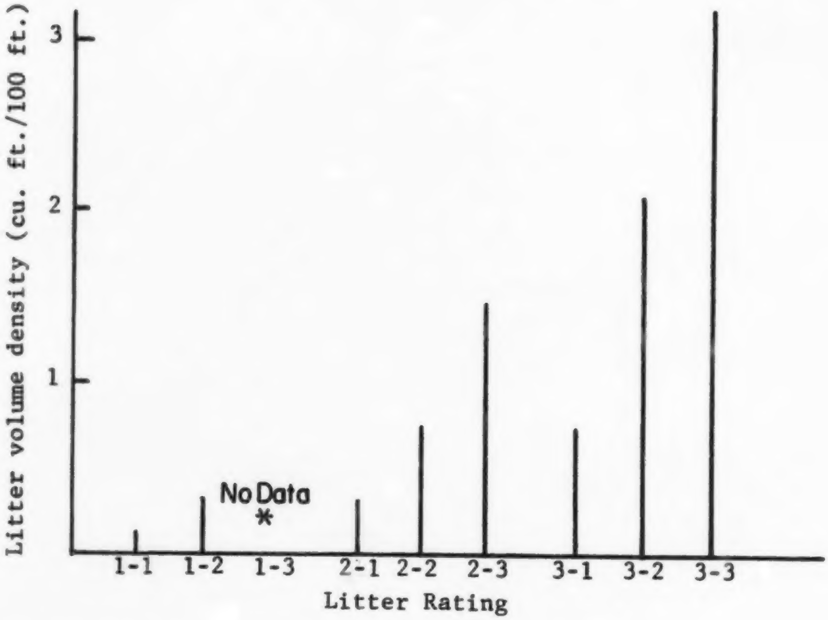

Figure 47. Litter volume density versus blockside ratings grouped according to % street littered

(% of curb littered). Each group is then ordered according to the second digit (size of litter). As expected, within each group the volume increases as the size of the litter increases; furthermore, the volume increases from group 1 to group 2 to group 3. The increases are not proportional but conform approximately to the nonlinear scale chosen in quantizing the data points (0-15%, 15-40%, 40-100%).

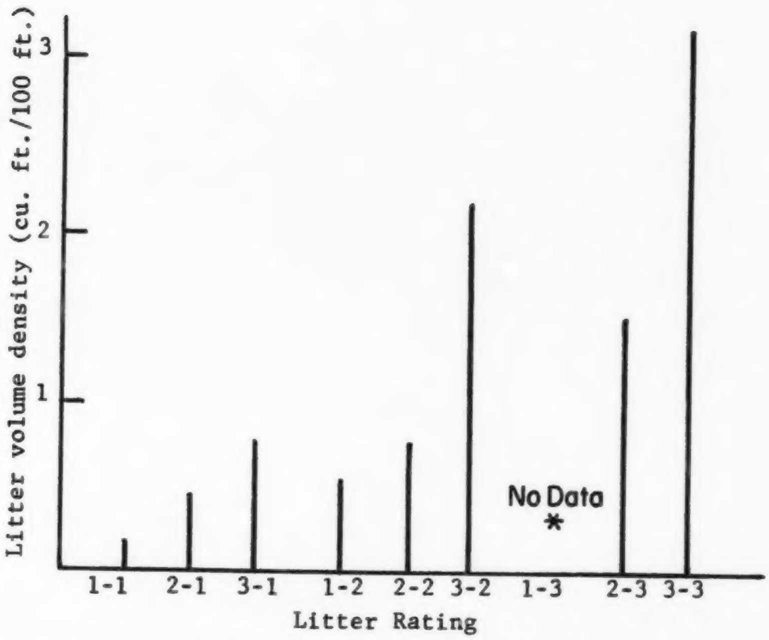

Figure 48. Litter volume density versus blockside rating grouped according to litter size.

In Figure 48 the results are grouped according to litter size, the second digit in the blockside rating. Again, for constant litter size, the litter volume increases as a larger fraction of the curb length is covered with litter. As the size increases, the volume also increases. Using these two figures, it was possible to extrapolate the data and obtain a value for the 1-3 rating.

Finally, certain combinations of % of curb littered and litter size yield approximately equal litter volume. The ratings 2-2 and 3-1 yield almost identical values for volume, while the 2-1 and 1-2 ratings are very close, well within the range of one standard deviation. These relationships are very useful because they reduce the number of distinct cases that need to be considered.

The second step in the procedure for determining the frequency of sweeping was the determination of the rate of litter generation, i.e., the conversions of the volume per unit length rating to volume per unit length per day. It was realized that the ratings for the blocksides depend on the time that had elapsed between the last sweeping and the time of data collection. Therefore, to every two digit rating a third digit was assigned indicating the number of days between the last sweeping and inspection. For example, if a blockside rated 1-1 had not been swept for three days at the time it was rated, then the extended rating would be 1-1-3.

The third digit, the number of days over which the measured litter volume had been accumulating, was computed for each and every blockside in the district. This was accomplished by comparing the time and day at which data were taken for a particular blockside with the parking regulation or regulations that were in force. The latter were obtained from the computer data bank. For example, if the blockside had an alternate side parking regulation, such as "No Parking on Monday and Thursday from 8 to 11 AM" and data were collected at 7 a.m. on Wednesday, then the time elapsed would be two days.

It was then assumed, in the absence of a better litter generation model, that litter increases linearly, i.e., it accumulates at a constant rate. For the purposes of this work, the linear model provided sufficient accuracy. The results of the first phase of an investigation to determine a litter generation model have been presented in Section IX.

From Table 14 a new table was constructed, Table 15, in which all the possible rates were tabulated. Since the maximum number of days between sweepings is four, the volume per unit length measure corresponding to each of the ratings was divided by 1, 2, 3, and 4. For example, in Table 14, the expected value of litter for a 1-1 rating is given as 0.027 ft^3 of litter per 100 ft. of curb. If a blockside was rated 1-1 after only one day had passed since it was last swept, then the corresponding rating 1-1-1 would be assigned the litter generation rate of 0.027 ft^3/100 ft./day. If two days had elapsed since the blockside was last swept, then the rating 1-1-2 would be assigned the value 0.0135 (=0.027/2). Similarly, the rate for 1-1-3 was calculated as 0.027/3 or 0.009 and for 1-1-4 as 0.0067 ft^3/100 ft./day. The complete results, ordered in terms of increasing litter generation rate, are shown in Table 15 and in graphical form in Figure 49. This is the basic information necessary to determine the frequency of sweeping on a rational basis.

Because of practical considerations in designing operatioal sets of sweeper routes, such as keeping the number of distinct routes and the number of different no-parking regulations small, it was decided to conform with present practice and use only three sweeping frequencies namely, two, three, or six times per week. Sweeping only once a week was considered unacceptable, even though some blocksides could be kept clean at that frequency because equipment failure, weather, or traffic conditions on the day that blockside is scheduled to be swept may result in a fifteen day period without service. All blocksides requiring sweeping more than three times a week and all metered areas were assigned the same frequency of six times per week (daily). This had the desirable effect of reducing the number of distinct routes that must be designed and then

Table 15. LIST OF LITTER GENERATION RATES AND CORRESPONDING RATINGS

Cubic Feet Per 100 Feet Per Day	Rating	Number of Days Unswept Prior to Inspection
0.0067	11	4
0.0090	11	3
0.0135	11	2
0.0270	11	1
0.0622	21	4
0.0802	12	4
0.0830	21	3
0.1070	12	3
0.1245	21	2
0.1570	31	4
0.1605	12	2
0.1612	22	4
0.2093	31	3
0.2350	22	3
0.2490	21	1
0.3100	23	4
0.3140	31	2
0.3210	12	1
0.3225	22	2
0.4133	23	3
0.5300	32	4
0.6200	23	2
0.6280	31	1
0.6450	22	1
0.7066	32	3
0.7500	33	4
1.000	33	3
1.060	32	2
1.240	23	1
1.515	33	2
2.120	32	1
3.030	33	1

learned by the operator.

Comparisons between the litter generation rates and the number of blocks in the experimental district that would correspond to each frequency for different threshold values led to the following assignments.

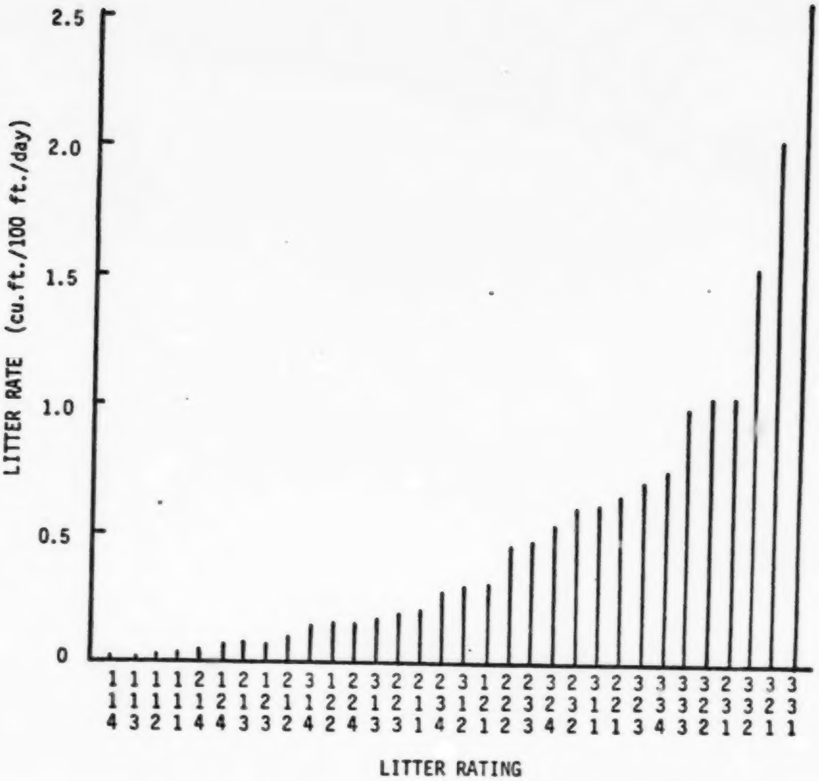

Fig. 49 Litter generation rate vs. litter ratings

(a) Blocksides with rates up to 0.315 ft^3/100 ft./day are to be swept two times per week.

(b) Blocksides with rates between 0.315 and 0.675 ft^3/100 ft./day are to be swept three times per week.

(c) Blocksides with rates higher than 0.675 ft^3/100 ft./day as well as all metered and half-metered blocksides are to be swept six times per week, i.e., daily except Sunday.

The two threshold values for the litter generation rate, 0.315 and 0.675, lead to the following statistics.

736 blocksides swept two times per week : 737 x 2 = 1472
135 " " three " " " : 135 x 3 = 405
298 " " six " " " : 298 x 6 = 1788
1169
3665

Since in one week 3665 blocksides are scheduled to be swept when the total number of blocksides in the district is 1169, it follows that on the average the district is serviced 3.2 times per week. This can be considered as a measure of the service provided by the Department of Sanitation; the corresponding value on the basis of current routes is 2.9 times per week. Although the two numbers are comparable, there is very substantial difference with regard to which blocksides are swept three or six times per week, the ones that need to be cleaned most. The proposed assignments of frequency of service represent actual current need, while the existing frequencies reflect past needs and have not taken into consideration changes in land use and population density, or urban development. There is no need for increased service; there is very definite need for reallocation of resources, i.e., not more sweepers but new sweeper assignments.

SECTION XI

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SECTION XII

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SECTION XIII

APPENDICES

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C. The Data Bank 150

APPENDIX A

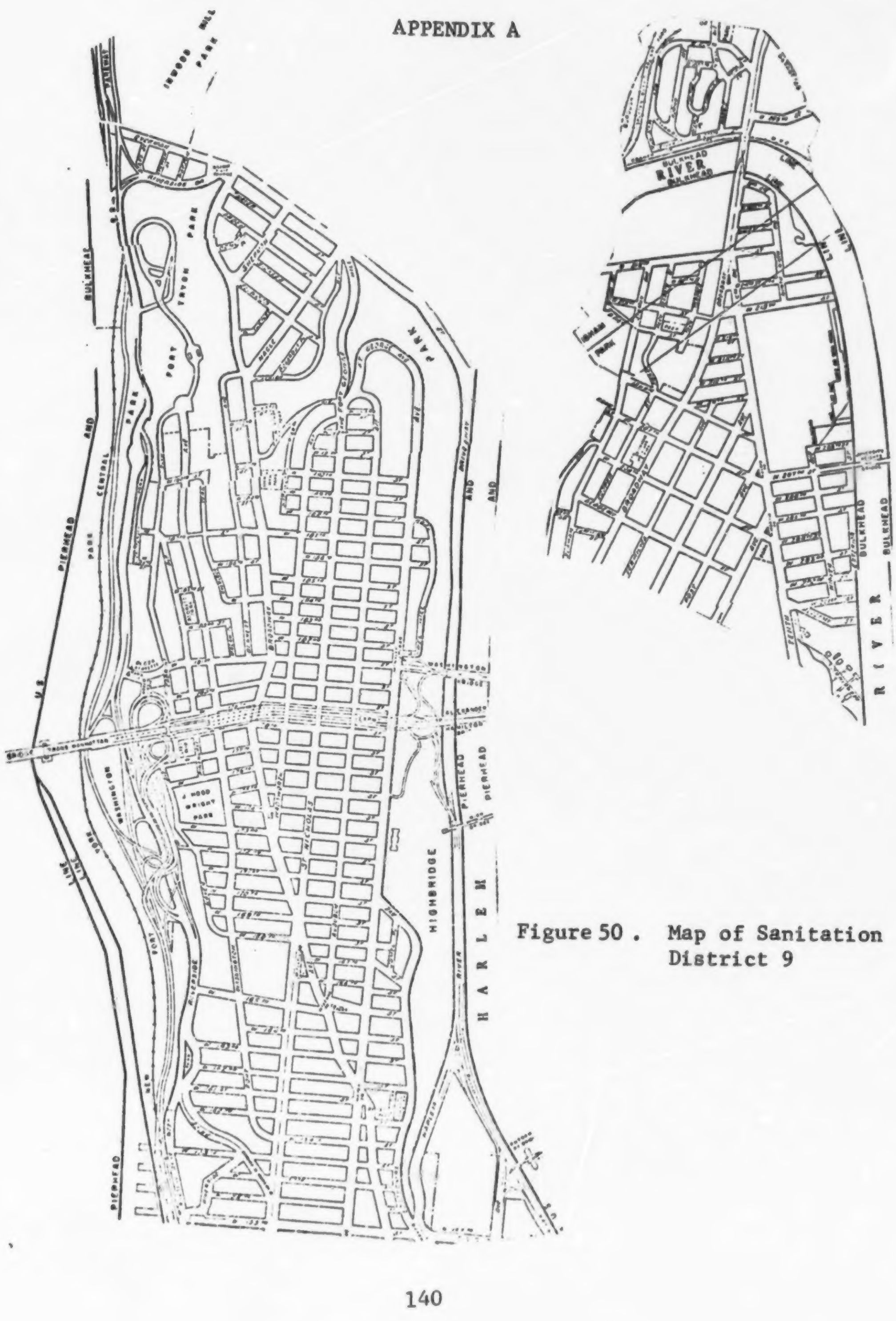
INWOOD HILL PARK
FORT TRYON PARK
J. HOOD WRIGHT PARK
HIGHBRIDGE
HARLEM RIVER
U.S. PIERHEAD AND BULKHEAD LINE
NEW YORK CENTRAL
FORT WASHINGTON PARK
RIVERSIDE
PIERHEAD
BULKHEAD
RIVER
RIVER

Figure 50 . Map of Sanitation District 9

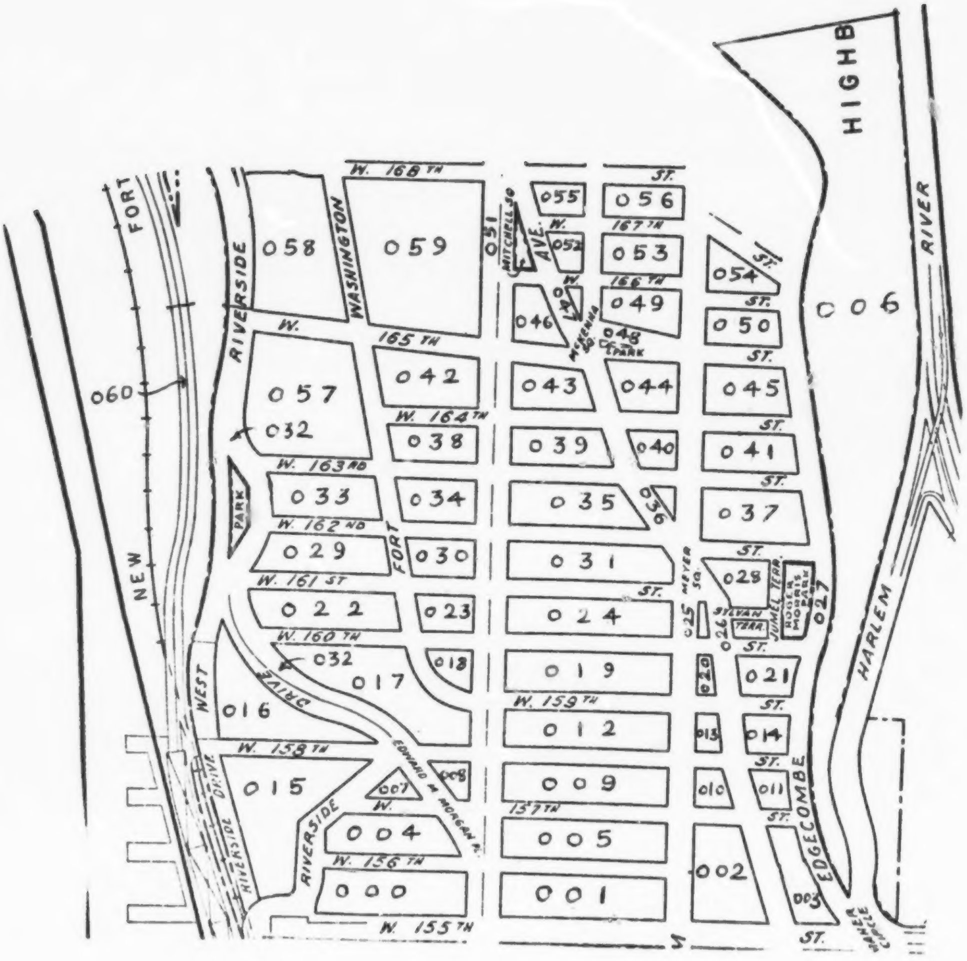
HIGHB
RIVER
HARLEM
NEW
FORT
060
W. 168TH
ST.
055
056
W.
167TH
058
RIVERSIDE
WASHINGTON
059
051
MITCHELL SQ
AVE.
052
053
054
ST.
W.
166TH
046
047
049
MCKENNA SQ
048
C.C.E. PARK
050
006
W.
165TH
057
042
043
044
045
W. 164TH
032
038
039
040
041
W. 163RD
PARK
033
034
035
036
037
W. 162ND
029
FORT
030
031
MEYER SQ.
028
JUMEL TERR.
ROGER MORRIS PARK
027
W. 161 ST
022
023
024
025
026
SYLVAN TERR.
W. 160TH
032
017
018
019
020
021
DRIVE
WEST
016
W. 159TH
012
013
014
W. 158TH
EDWARD M. MORGAN PL.
008
007
009
010
011
015
W.
157TH
RIVERSIDE
DRIVE
RIVERSIDE
004
005
002
EDGECOMBE
W. 156TH
000
001
003
DONAHER CIRCLE
W. 155TH
ST.

Figure 51. Map of Section 91

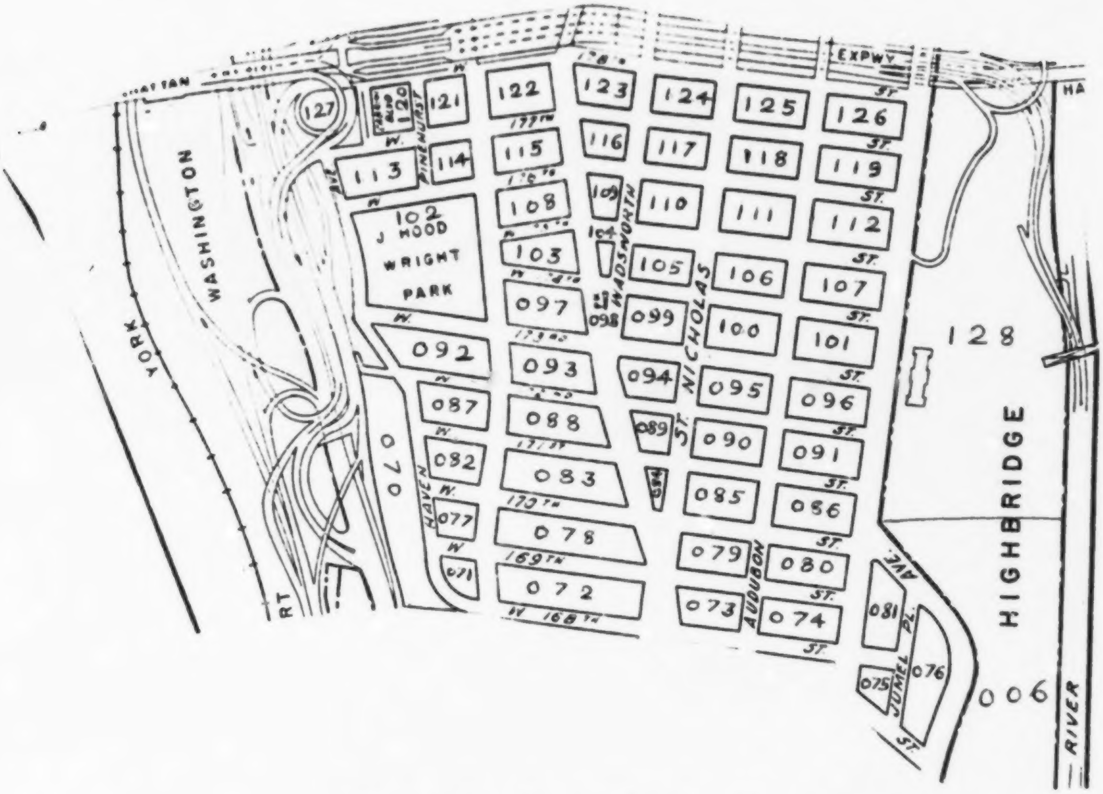
EXPWY
HIGHBRIDGE
RIVER
YORK
WASHINGTON
J HOOD WRIGHT PARK
WADSWORTH
ST. NICHOLAS
AUDUBON
HAVEN
PINEHURST
JUMEL PL.
AVE.
128
006
070
102
127
120
121
122
123
124
125
126
113
114
115
116
117
118
119
108
109
110
111
112
103
104
105
106
107
097
098
099
100
101
092
093
094
095
096
087
088
089
090
091
082
083
084
085
086
077
078
079
080
081
071
072
073
074
075
076
W. 168TH
169TH
170TH
177TH
ST.

Figure 52 . Map of Section 92

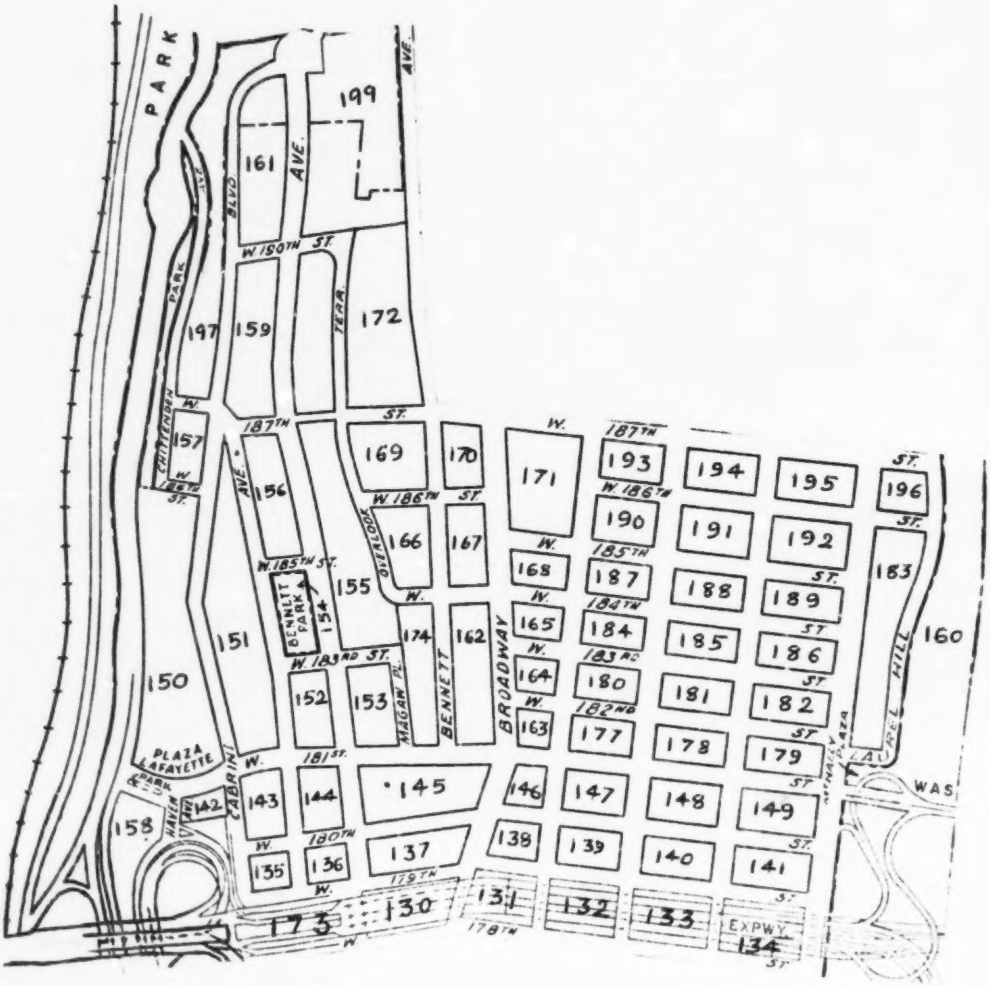
PARK
199
AVE.
161
BLVD
AVE.
W. 190TH ST.
197
159
TERR.
172
CHITTENDEN
PARK AVE.
W.
157
W. 188TH ST.
187TH ST.
169
170
W. 187TH
171
193
194
195
ST.
196
AVE.
156
W. 186TH ST.
OVERLOOK
166
167
W. 186TH
190
191
192
ST.
W. 185TH ST.
BENNETT PARK
154
155
W.
168
185TH
187
188
ST.
189
183
151
174
162
BROADWAY
W.
165
184TH
184
185
ST
186
160
W. 183RD ST.
W.
164
183RD
180
181
ST
182
150
152
153
MAGAW PL.
BENNETT
W.
163
182ND
177
178
ST.
179
PLAZA LAFAYETTE
CABRINI
W.
181ST.
143
144
145
146
147
148
ST.
149
PLAZA
LAUREL HILL
WAS
& PARK
HAVEN
142
158
W.
180TH
135
136
137
138
139
140
ST.
141
W.
179TH
173
130
131
132
133
EXPWY.
134
W
178TH
ST.

Figure 53. Map of Section 93

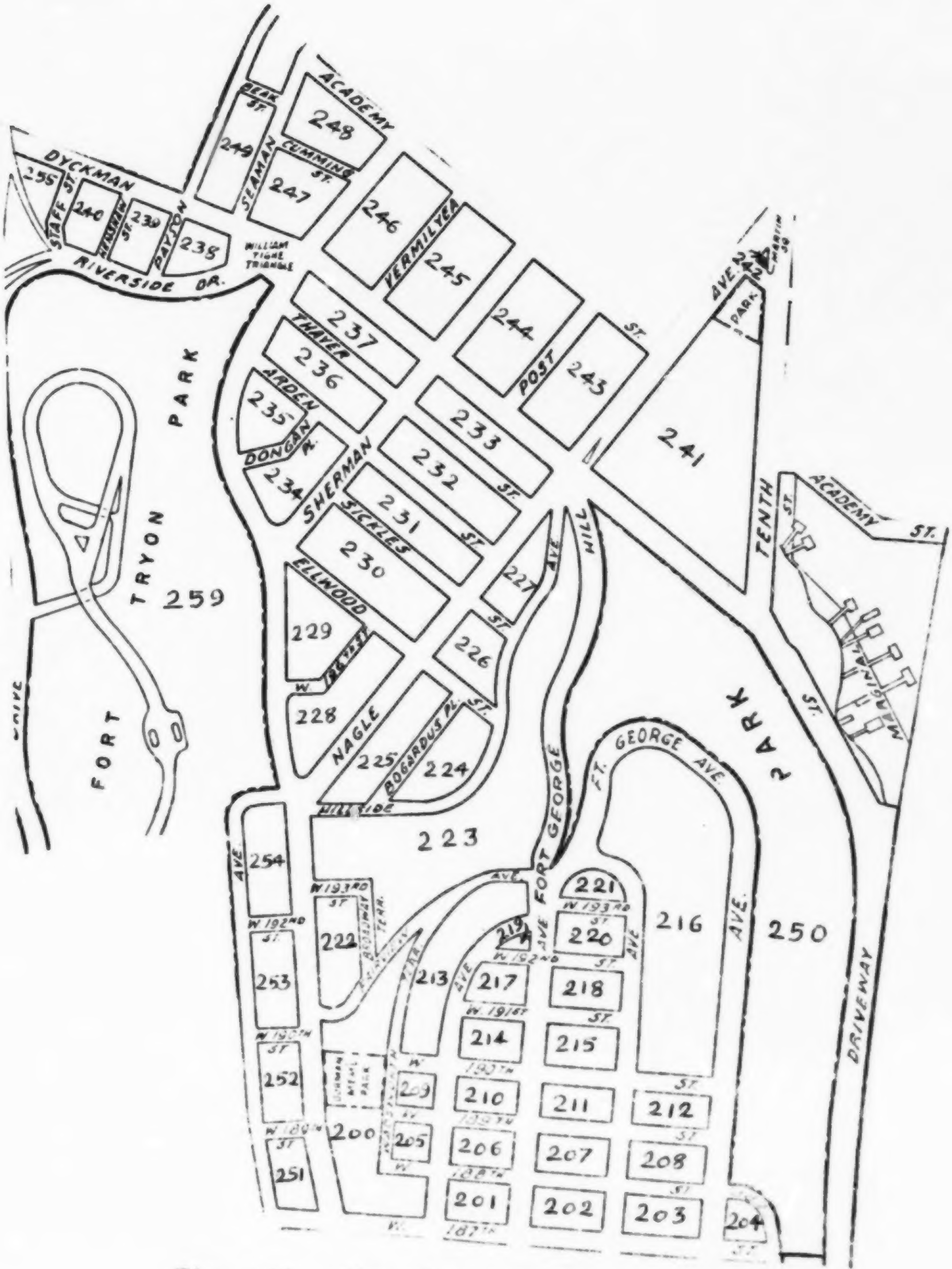
ACADEMY
248
BEAK ST.
249
SEAMAN
CUMMING ST.
247
DYCKMAN
255
STAFF ST.
240
ST.
239
PAYSON
238
WILLIAM TIGHE TRIANGLE
RIVERSIDE DR.
246
VERMILYEA
245
244
POST
243
ST.
AVE.
PARK
237
THAYER
236
ARDEN
235
DONGAN PL.
234
SHERMAN
233
232
ST.
231
SICKLES
ST.
241
230
ELLWOOD
227
ST.
229
226
W. 193RD ST.
228
NAGLE
225
BOGARDUS PL.
ST.
224
HILLSIDE
223
HILL
AVE
FORT GEORGE
AVE
TENTH
ACADEMY ST.
ST.
MARGINAL
ST.
PARK
FORT TRYON PARK
259
DRIVE
FT. GEORGE AVE
AVE.
254
W 193RD ST
222
BROADWAY TERR.
AVE
221
W.193RD ST
220
AVE
216
AVE.
250
219
W.192ND ST
217
218
213
W.192ND ST.
253
W.191ST ST.
214
215
W.190TH ST
252
DYCKMAN MEM'L PARK
W.
190TH
209
210
211
212
ST.
W.189TH ST
200
205
AV
206
189TH
207
208
ST.
W.
188TH
ST.
251
201
202
203
204
W.
187TH
ST.
DRIVEWAY

Figure 54. Map of Section 94

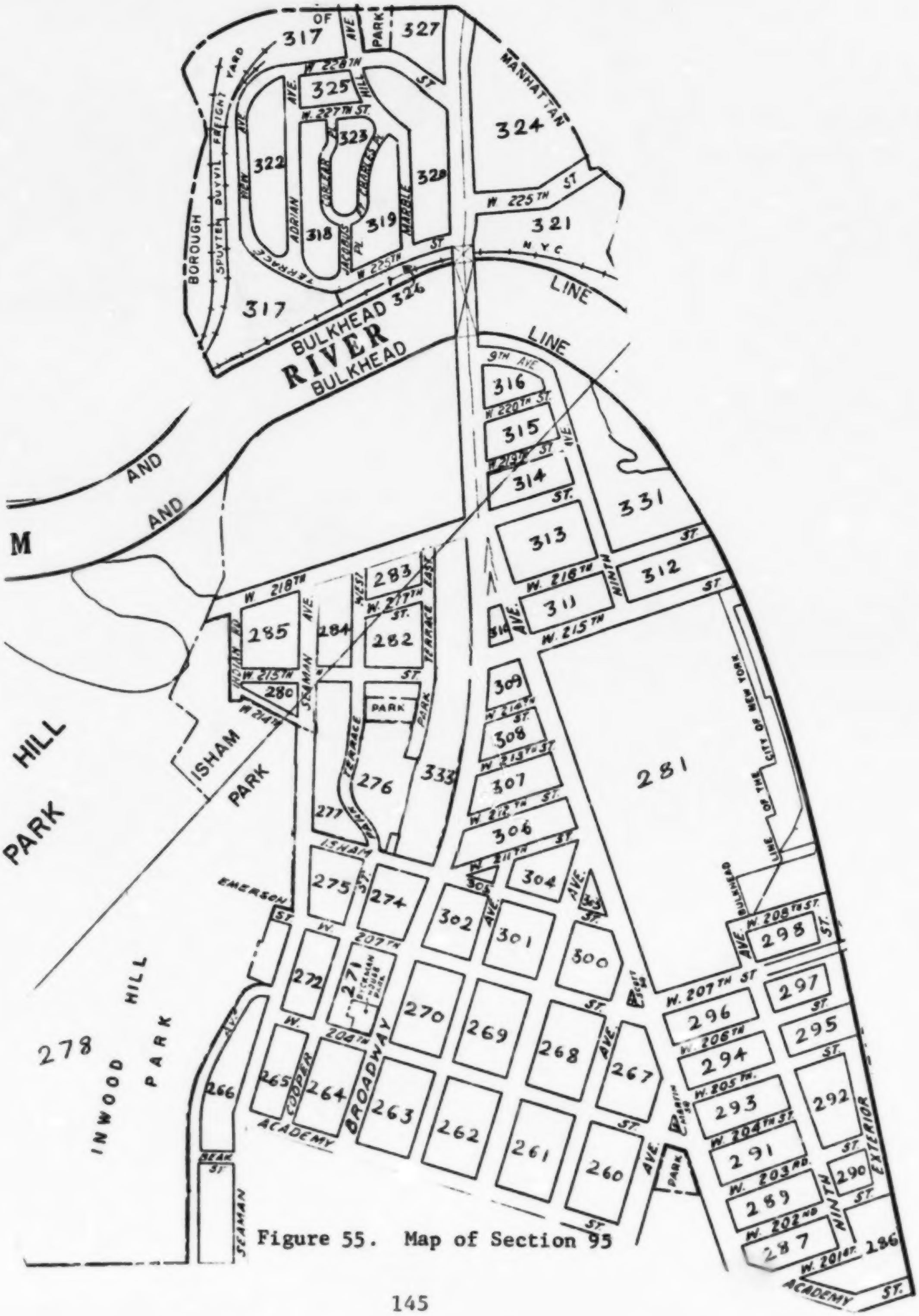
317
OF
AVE
PARK
327
W. 228TH
325
AVE
HILL
ST
MANHATTAN
W. 227TH ST.
323
324
322
BROADWAY
ADRIAN
TERRACE
PL
MARBLE
320
319
318
W 225TH ST
321
N.Y.C.
BOROUGH
SPUYTEN DUYVIL FREIGHT YARD
W. 225TH ST
317
326
BULKHEAD
LINE
RIVER
BULKHEAD
LINE
9TH AVE
316
W. 220TH ST.
315
AVE
W. 219TH ST
314
ST.
331
AND
AND
M
313
ST
W. 218TH
W. 218TH
NINTH
312
ST
283
W. 217TH
ST.
311
W. 215TH
AVE.
310
285
284
282
INDIAN RD
SEAMAN AVE
W. 215TH
ST.
280
PARK
W 214TH
309
W. 214TH
308
W. 213TH ST
HILL
ISHAM
TERRACE
276
333
PARK
307
W. 212TH ST.
281
CITY OF NEW YORK
PARK
277
306
W. 211TH ST
ISHAM
BULKHEAD
LINE OF THE
EMERSON
275
274
ST.
305
304
AVE.
303
ST
W. 207TH
302
AVE.
301
AVE.
W. 208TH ST.
298
300
ST.
272
271
W. 207TH ST
297
ST.
270
269
268
296
W. 206TH
295
ST.
294
HILL
278
INWOOD
PARK
W.
204TH
AVE.
267
W. 205TH
293
292
266
265
COOPER
264
BROADWAY
263
262
261
ACADEMY
W. 204TH ST
291
ST
W. 203RD
290
EXTERIOR
ST.
260
AVE.
PARK
BEAK ST
SEAMAN
289
W. 202ND
NINTH
ST.
287
W. 201ST.
286
ACADEMY
ST.

Figure 55. Map of Section 95

APPENDIX B

LIST OF ODD-SHAPED BLOCKS

Blockside	
Section 91	
0063	Edgecombe Ave. (E. Side) from W. 155 St. North to Amsterdam Ave.
0167	Riverside Dr. (W. Side) from Edward Morgan Pl. to Riverside Dr. W.
0170	Ft. Washington Ave. - W. Side - from Broadway North to W. 160th St.
0177	Broadway (W. Side) from W. 156th St. North to Ft. Washington Ave.
0283	St. Nicholas Ave. (E. Side) from W. 160th St. North to W. 162 St. (026 has no "3" side).
0323	Riverside Dr. (lower roadway) from W. 156 St. North to W. 165 St.
0328	Riverside Dr. (service rd - upper roadway) from W. 158th St. North to W. 165th St.
0587	Riverside Dr. (E. Side) from W. 165 St. North to I-95 entrance.
0607	Riverside Dr. West and Riverside Dr. (water side) from W. 155 St. North to W. 165 St.
Section 92	
0703	Haven Ave. (W. side) from Broadway north to W. 178 St.
0707	Approach to I-95 (George Washington Br. & Cross Bronx Expwy) (E. Side) from Riverside Dr. North to W. 178 St.
0815	W. 170 St. & Edgecombe Ave. (S & W. Sides) from Amsterdam Ave. to Jummel Pl.
1283	Amsterdam Ave. (E. Side) from Edgecombe Ave. North to Washington Bridge at W. 181 St.
Section 93	
1503	Riverside Dr. (Entrance to Henry Hudson Pkwy.) from W. 181 St. North to Parkway.
1505	Chittenden Ave. and W. 186 St. (W. and N. Sides) from W. 187th St. to Cabrini Blvd.

Section 93 (cont.)

1511	W. 181 St. (N. Side) from Ft. Washington Ave. West to Cabrini Blvd. (152 has no "1" side).
1552	W. 183 St. (N. side) from Ft. Washington Ave. to Magaw Pl.
1557	Overlook Terrace (W. side) from W. 190 St. south to W. 184 St.
1603	Laurel Hill Blvd. and W. 182 st. (E. and S. sides) from Amsterdam and W. 182 St. north to Amsterdam and W. 188 St.
1727	Bennett Ave. (W. side) from W. 187 St. north to W. 190 St.
1745	W. 184 St. (S. side) from Overlook Terrace to Bennett Ave.
1978	Cabrini Blvd. (W. side) from W. 187 St. north to Ft. Tryon Park Circle.
1991	W. 190 St. (N. side) from Ft. Washington Ave. to Overlook Terrace.
1993	Ft. Washington Ave. (E. side) from W. 190 St. north to Ft. Tryon Circle.
1997	Bennett Ave. (W. side) from W. 190 St. north to Broadway.

Section 94

2000	Wadsworth Terrace and W. 188 St. (W. and S. sides) from Fairview Ave. to Wadsworth Ave.
2005	Fairview Ave. (S. side) from Broadway to Wadsworth Terrace.
2007	Wadsworth Ave. (W. side) from W. 187 St. to W. 188 St.
2137	Broadway (N. side) from Fairview Ave. to Wadsworth Ave.
2163	Audubon Ave. (E. side) from W. 190 St. north to Ft. George Ave.
2167	Ft. George Ave. and Amsterdam Ave. (N. and W. sides) from W. 190 St. to Ft. George Hill.
2231	Fairview Ave. (W. side) from Broadway Terrace to St. Nicholas Ave.
2233	Broadway (E. side) from W. 193 St. north to Hillside Ave.
2234	W. 194 St. and Broadway Terrace (N. and E. sides) from Broadway to Fairview Ave.
2235	Hillside Ave. (N. and E. sides) from Broadway to Ft. George Hill.
2237	Ft. George Hill (W. side) from Fairview Ave. to Hillside Ave.

Section 94 (cont.)

2281	Broadway (E. side) from Nagle Ave. to W. 196 St.
2283	W. 196 St. from Broadway to Ellwood St.
2285	Ellwood St. from W. 190 St. to Nagle Ave.
2287	Nagle Ave. from Ellwood Ave. to Broadway.
2293	Broadway (E. side) from W. 196 St. to Ellwood Ave.
2295	Ellwood St. from Broadway to W. 196 St.
2297	W. 156 St. from Ellwood St. to Broadway.
2341	Broadway from Sherman Ave. to Dongan Place.
2343	Dongan Pl. from Broadway to Arden Place.
2345	Arden Pl. from Dongan Pl. to Sherman Ave.
2347	Sherman Ave. from Broadway to Arden Place.
2353	Broadway (E. side) from Dongan Pl. to Arden St.
2355	Arden St. from Broadway to Dongan Place.
2358	Dongan Pl. from Broadway to Arden St.
2500	Amsterdam Ave. and Ft. George Ave. (E. and N. sides) from Laurel Hill Terrace to St. Nicholas Ave.
2503	Ft. George Hill from St. Nicholas Ave. to Dyckman St.
2505	Dyckman St. from Ft. George Hill to Harlem River Drive.
2595	Riverside Dr. (S. side) from Henry Hudson Pkwy. exit to Broadway.
2597	Broadway (N. side) from Bennett Ave. to Riverside Drive.

Section 95

2670	Tenth Ave. from W. 207 st. to Nagle Ave.
2677	Nagle Ave. from Tenth Ave. to W. 204 St.
2780	Dyckman St. (N. side) from Payson Ave. to Dead End.
2781	Payson Ave. (W. side) from Dyckman St. to Seaman Ave.
2785	Seaman Ave. (W. side) from W. 207 St. to W. 214 St.
2787	W. 214 St. (S. side) from Seaman Ave. to Indian Rd.
2789	Indian Rd. (W. side) from W. 214 St. to W. 218 St.
2817	Ninth Ave. (W. side) from W. 207 St. to W. 208 St.
3177	W. 228 St. and Terrace View Ave. (N. and W. sides) from Marble Hill Ave. to W. 225 St.
3205	W. 228 St. (S. side) from Marble Hill Ave. to Broadway.

Section 95 (cont.)

3265	W. 225 St. (S. side) from Terrace View and Adrian Aves. to Broadway.
3900 3909	Henry Hudson Pkwy. from W. 155 St. to Henry Hudson Bridge approach.
3910 3919	Harlem River Dr. from W. 155 St. to Dyckman St.
3920	Broadway Mall (both sides) from W. 155 St. to W. 168 St.
3930	All access roads in Ft. Tryon Park.

APPENDIX C

THE DATA BANK

Table 16. SAMPLE OF DATA BANK LISTING (1st SET)

Block Code	Total Length	Illeg. Length	Park. Space	Park Reg.	Str. Width	Land Use	Litter Rating	Volume Rate
0001	675	158	21	5	100	14444	121	0.3209
0003	210	70	5	6	150	11111	111	0.0269
0005	630	40	24	6	10	14448	122	0.1604
0007	200	76	8	9	150	44444	121	0.3208
0011	775	298	19	1	100	13344	111	0.0268
			.	.	.			

Table 17. SAMPLE OF DATA BANK LISTING (2nd SET)

Block Code	Census Tract	Tract Pop.	Crowd Index	House Units	Median Age	Median Income	Cens. Block	Block Pop.
0001	241.00	8232	0.62	2871	39.11	5284	201	554
0003	241.00	8232	0.62	2871	39.11	5284	201	554
0005	241.00	8232	0.62	2871	39.11	5284	201	554
0007	241.00	8232	0.62	2871	39.11	5284	201	554
0011	241.00	8232	0.62	2871	39.11	5284	103	917
			.	.	.			